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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**E-BOMB: THE KEY ELEMENT OF THE CONTEMPORARY
MILITARY-TECHNICAL REVOLUTION**

by

Necati Ertekin

September 2008

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**E-BOMB: THE KEY ELEMENT OF THE CONTEMPORARY
MILITARY-TECHNICAL REVOLUTION**

Necati Ertekin
Lieutenant, Junior Grade, Turkish Navy
B.S., Turkish Naval Academy, 2003

Submitted in partial fulfillment of the
requirements for the degrees of

**MASTER OF SCIENCE IN ELECTRONIC WARFARE SYSTEMS
ENGINEERING**

and

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ABSTRACT

The contemporary military rivalry is driven mostly by the ongoing military technical revolution. In particular, the weapons used on the future battlefield will play an important role in military affairs. Which weapons can play a key role in the future? Electromagnetic weapons seem to involve key elements for the future battlefield; they offer advantages over conventional weaponry by providing nonlethality, the advantage of attack at the speed of light, fast engagement of multiple targets, potentially low operational cost, and wide-area coverage for offensive and defensive purposes.

This thesis proposes hypothetical electromagnetic bombs (e-bomb) and classifies e-bombs into three isocategories depending on power sources. It also assesses the potential lethality effects on different targets based on a developed MATLAB Simulation Model. It also provides an understanding of the principles of High Altitude Electromagnetic Pulse (HEMP) and High Power Microwave (HPM) Weapons. In addition, a measure of effectiveness model is proposed to compare the hypothetical e-bomb, HEMP and HPM weapons. The strategic effects on military affairs will be assessed. Finally, this study will help the Turkish Armed Forces decide on investment in e-bomb research and development (R&D) to improve combat capabilities in the future battlefield.

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EXECUTIVE SUMMARY

The future battlefield will involve warfare using new generation weapons such as electromagnetic weapons. The increasing costs of conventional weapons, combined with the lethal effects on humans and the environment, leads global powers into the exploration of relatively cheap and nonlethal weapons. In addition, the increasing dependency of conventional weapons on command and control systems creates a weakness because the technology used in command and control system is mostly susceptible and vulnerable to electronic transient generated by electromagnetic weapons. This thesis proposes a new electromagnetic-bomb (e-bomb).

An electronic bomb, or e-bomb, is a form of directed energy with potential for military utility. Even though the e-bomb currently is not completely described in open literature sources, sufficient information has been published about e-bomb technology by directed energy researchers to support the general impression that electromagnetic weapons could be built. In this study, High Power Microwave (HPM) basic transmission theory will be used to define the characteristic of a hypothetical e-bomb. In addition, High Altitude Electromagnetic Pulse (HEMP) and HPM weapons will be also defined in order to assess the effectiveness of a proposed hypothetical e-bomb in comparison with other electromagnetic weapons.

To show a wide range of different applications, source technologies and the range of effects on different targets, three types of e-bombs will be categorized and evaluated:

- Low-Tech (Small) E-Bomb (intended to be used against unshielded systems)
- Medium-Tech (Moderate) E-Bomb (intended to be used against moderately shielded systems, commercial aircrafts for example)

- High-Tech (Powerful) E-Bomb (intended to be used against fully shielded systems, such as military assets)

The HPM theory, currently defined in open literature, will be used to assess the potential lethality and upset effect of a proposed e-bomb on electronic systems. This theory as described will also be the basis for MATLAB simulation calculation. Once the simulation model is generated, the High Intensity Radiated Field (HIRF) standards, which are established in order to define the maximum field strength in which commercial airplanes can safely fly, and the published damage threshold levels for representative electronic devices will be used as tools to validate the model. If the electric field strength, which is defined in HIRF standards as “severe” for commercial airplane for designated frequency, is proved to be sufficient to possibly damage the representative electronic devices, the model will be assumed as “validated.”

Once the model is validated, the simulation will be run for each type of proposed e-bomb in order to assess the potential lethality against different kinds of targets.

After assessing the effects of a proposed e-bomb, defense against e-bombs and the military utility, including advantages and disadvantages, will be identified in order to evaluate the limitations and the potential benefits of hypothetical e-bombs.

The next step in this thesis is to define the importance of the hypothetical e-bomb in military rivalry. The military rivalry mostly depends on military technical revolution. The weapons that will be used in the future battlefield will play an important role in military rivalry. Since the proposed e-bomb offers advantages over conventional weapons by providing a) nonlethality (no damage on humans), b) attack at the speed of light, c) fast engagement of multiple targets, d) potential low operational cost, and e) area coverage for offensive and defensive purposes, it is possible that the hypothetical e-bomb will be a key element for the battlefield of the future.

Multiple, objective decision making provides a good methodology to assess the role of proposed e-bomb in military rivalry. Since the factors that affect the use/choice of a weapon instead of alternatives, are numerous and diverse, multiple, objective decision making will provide a better approach to compare similar weapons. In this study, one of the multiple, objective decision making methods, the “cost-effectiveness analysis,” will be used to compare the electromagnetic weapons. A “measure of effectiveness” model for electromagnetic weapons will be introduced. The model will mostly include qualitative measurement because there is not enough open source information available to define the attributes. Another limitation in this analysis is the cost estimation of such weapons. Since there is not enough source data to define the cost of each individual weapon, the cost issue in the analysis will be assumed equal. Even though such limitations exist, the output of the cost-effectiveness model will provide a good vision in order to assess the future benefits of proposed e-bomb.

The implementation of such a weapon (potentially the weapon of the future battlefield), will definitely change the position of any military force in the military rivalry. Finally, under the assumptions made and conditions defined, the implementation of a hypothetical e-bomb to the Turkish Armed Forces will be analyzed. The potential benefits from such a weapon will be introduced and the reasons why the Turkish Armed Forces should invest in e-bomb research and development (R&D) will be identified.

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I. INTRODUCTION

A nation which does not practice science, such a nation, one must admit has no place in the high road of civilization.

— Mustafa Kemal Atatürk
The founder and the first president of the Turkish Republic

In 1232, during the battle of Kai-Keng, the Chinese repelled Mongol invaders with the first known use of rudimentary rockets powered by gunpowder, called “arrows of flying fire.”

In 1914, employing automatic weapons, the German army rolled across Europe, dominating the cavalry and breech-loaded armies that made up the conventional forces of that era.

On August 9, 1945, a lone American B-29 bomber flew over Nagasaki, Japan, and dropped a single atomic bomb that ended World War II.

And in February 1991, precision-guided “smart” bombs, ground-hugging cruise missiles, and invisible stealth fighters forced the massively equipped and much more numerous Iraqi army to its knees.

In 2003, the conflict in Iraq just missed seeing the introduction of a new generation of sophisticated weaponry.

These overwhelming victories had one thing in common: They exploited technology to underpin a revolution in military affairs. Today the next revolution in military affairs is about to begin. But this revolution is not built on bombs or bullets, or anything you can hold in your hands. It comes from the same spectrum of energy found in a microwave, a light bulb, or a TV remote control. It is called Directed Energy (Beason, 2005).

A. AREA OF RESEARCH

The next revolution in military affairs is about to begin. This revolution may have munitions whose effects are not kinetic, but may instead be based on directed and focused energy. An electronic bomb, or e-bomb, is a form of directed energy with potential for military utility.

Even though the e-bomb is not completely described in open literature sources, directed energy researchers have published sufficient information about the underlying technology to indicate that electromagnetic weapons could be built (Kopp, 1993) (Kopp, 1996) (Benford, Swegle, and Schamiloglu, 2007). If so, the e-bomb has potential to change significantly the international correlation of forces.

This thesis researches the technical aspects of the e-bomb, explores its potential capabilities, and assesses the effects on contemporary military rivalries.

B. MAJOR RESEARCH QUESTIONS

1. Primary Question

— Should Turkish Armed Forces invest in e-bomb research and development (R&D) to improve combat capabilities in the battlefield of the future?

2. Subsidiary Questions

— What is the e-bomb, what reasonable outputs can be expected and what are the soft kill and hard kill conditions associated with such a device?

— What measures protect targets from e-bomb attack?

— How does the e-bomb compare to other forms of high-power electromagnetic weaponry?

— What does a first order model for evaluating the Measure of Effectiveness (MOE) of different capability levels of e-bombs tell us about potential military utility?

C. IMPORTANCE AND THE BENEFITS OF THE STUDY

The results of this study may be used to support ongoing efforts by Turkish Armed Forces to apply electronic warfare and other countermeasures against modern threats. This thesis should enhance the perspective and knowledge of electronic warfare officers, technical personnel and policy makers. Furthermore, research and results will assist the Turkish Armed Forces in evaluating the needs and requirements of electronic warfare systems for the battlefield of the future.

D. ORGANIZATION OF THE THESIS

This thesis is composed of six chapters. Chapter I provides an introduction to, and an overview of, new technology weapons of future battlefield, the electromagnetic-bomb.

Chapter II presents the fundamental terminology for directed energy weapons and electromagnetic weapons, and provides the historical background for each of these weapons. In addition to providing the definitions in order to understand directed energy and electromagnetic weapons clearly, High Altitude Electromagnetic Pulse (HEMP) and High Power Microwave (HPM) weapons is briefly explained in order to compare them with the hypothetical e-bomb, which are discussed in Chapter III.

Chapter III introduces three kinds of e-bombs, defines e-bomb theory, gives the specification for each class, and defines a MATLAB model used to simulate each type of e-bomb. It also validates the proposed simulation model according to a given scenario and evaluates a bound on the potential lethality range of each type of e-bomb based on the known susceptibility levels of possible

targets. In addition, countermeasures against e-bombs and the overall military utility of such a weapon are analyzed in this chapter.

Chapter IV explains multiple objective decision methods, defines the estimation of measure of effectiveness of any system, proposes a measure of effectiveness model to compare electromagnetic weapons and evaluates the benefits of three electromagnetic weapons (HEMP, HPM and E-Bomb) according to the output of the model. Furthermore, potential advantages and attractiveness of the e-bomb are assessed, in comparison with other electromagnetic.

Chapter V discusses the battlefield of the future, the importance of e-bombs, the military rivalry at present and in the near future and the potential effect of an e-bomb in military affairs. Furthermore, this chapter answers the primary research question whether the Turkish Armed Forces should invest in e-bomb research and development (R&D) to improve its combat capabilities in the battlefield of the future.

Chapter VI presents the conclusion of the study and suggests recommendations for future thesis work.

Figure 1 shows the outline of the thesis.

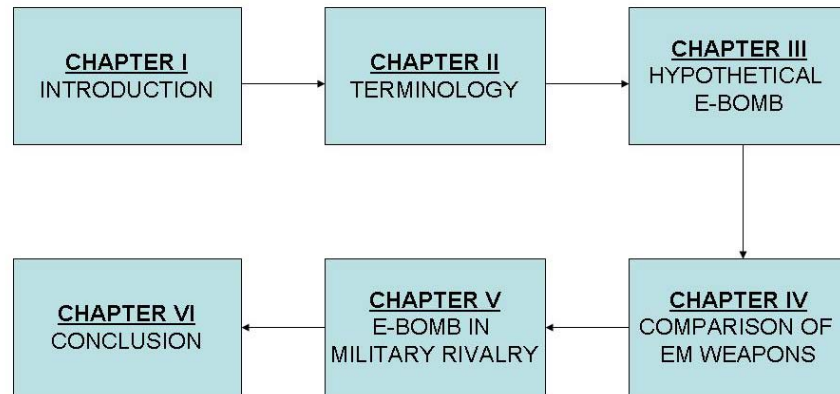


Figure 1. Thesis Roadmap

II. TERMINOLOGY

I am not leaving a spiritual legacy of dogmas, unchangeable petrified directives. My spiritual legacy is science and reason. ... What I wanted to do and what I tried to achieve for the Turkish nation is quite evident. If those people who wish to follow me after I am gone take the reason and science as their guides they will be my true spiritual heirs.

— Mustafa Kemal Atatürk

A. BACKGROUND

An electronic bomb, or e-bomb, is a form of directed energy device with potential for military applications. Even though the e-bomb currently is not completely described in open literature sources, sufficient information has been published (Kopp, 1993) (Kopp, 1996) (Benford, Swegle, and Schamiloglu, 2007) about e-bomb technology by directed energy researchers to indicate that electromagnetic weapons could be built.

Directed Energy research originated with research work done to determine the impact to important military systems operating in harsh electromagnetic environments. One of the most threatening and pervasive of all electromagnetic threats is that due to electromagnetic pulses.

The electromagnetic pulse produced by a high-altitude nuclear detonation can induce electrical stresses (currents, voltages, or charge) on and within systems. These HEMP induced stresses can damage or severely disrupt some electronic systems, which are sensitive to transient disturbance. Significant potential damaging effects can occur at long ranges to virtually all systems located within line-of-sight of the detonation point.

The first electromagnetic pulse effect was observed during a high altitude airburst nuclear weapons testing. As a result of the test, a very short but extremely intense electromagnetic pulse was observed. This pulse propagated away from its source with a decreasing intensity, which is also to be expected

according to the theory of electromagnetism. Carlo Kopp, a prominent Australian freelance defense analyst and academic, defined this electromagnetic pulse as “an electromagnetic shock wave” (Kopp, 1993). An unclassified representation of the electromagnetic pulse normalized amplitude versus the pulse duration for the e-bomb available in the open literature (Kopp, 1996) is shown in Figure 2 and contrasted with those of the unclassified representation of the nuclear electromagnetic pulse transient and a typical lightning stroke. It can be seen in this plot that the Flux Compression Generator, that is intended to be one of the power sources for the proposed e-bomb and will be explained later, share similar spectral content with a nuclear electromagnetic transient and lightning stroke. The higher pulsewidth of Flux Compression Generator can also provide extra advantages such as better coupling efficiency. However, it may be disadvantage since it causes less atmospheric breakdown level than others. The technical detail will be explained in later chapters.

Taylor and Giri, the authors of a book named: “High Power Microwave Systems and Effects,” mention about an interesting example of electromagnetic effect in their book:

A tragic example of the effects on electronics from high power microwave (HPM) illumination occurred on the U.S. aircraft carrier Forrestal on July 29, 1967. At that time, the Forrestal was cruising off the coast of North Vietnam. It's A-4 Skyhawk jets had flown more than 700 sorties. A number of A-4's were on the deck, fully fueled and loaded with 1000-lb bombs, air-to-ground missiles, and air-to-air missiles. One of the missile cables apparently had an improperly, mounted shielded connector. When it was illuminated by a shipboard radar, RF voltages were developed in the degraded connector which resulted in a missile being fired across the deck and striking another aircraft. Secondary explosions of aircraft, bombs, and missiles did \$72 million of damage, with 134 men lost or missing (Taylor and Giri, 1996).

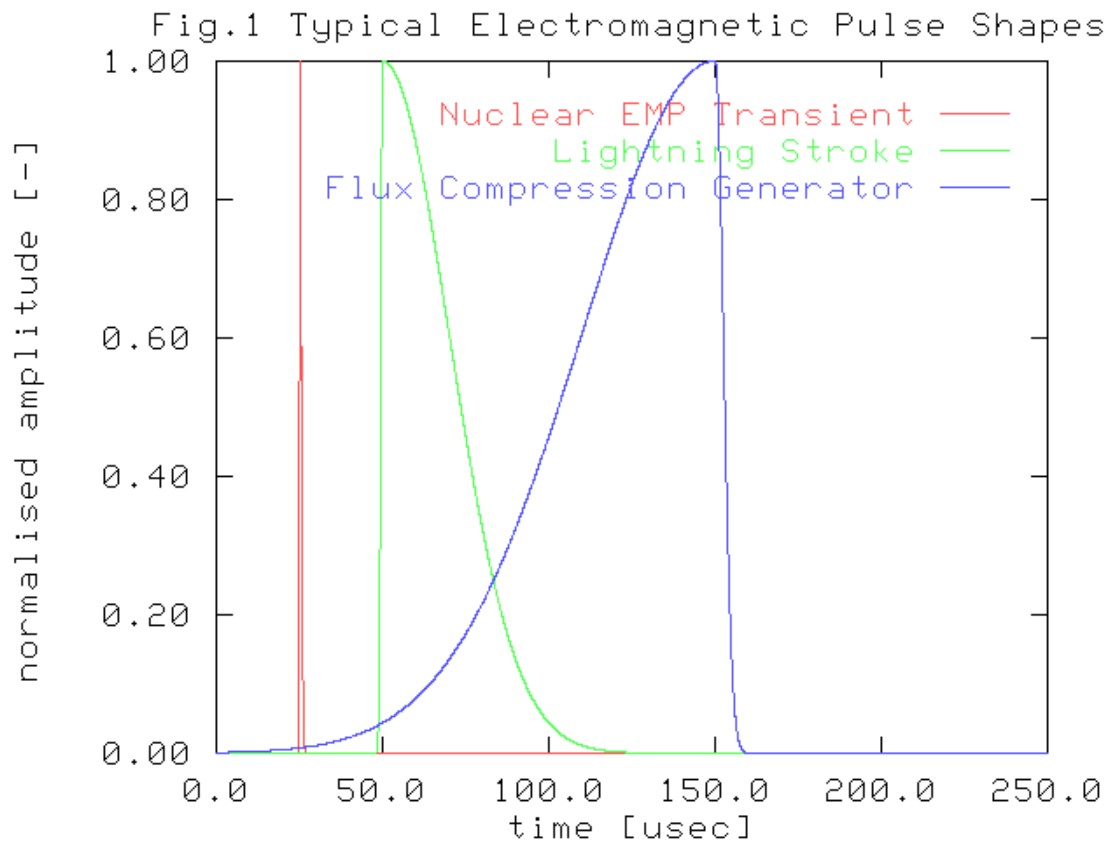


Figure 2. Typical Electromagnetic Pulse Shape (Kopp, 1996)

On March 25, 2003, CBS News reported that

The U.S. Air Force hit Iraqi TV with an experimental electromagnetic pulse device called the “E-Bomb” in an attempt to knock it off the air and shut down Saddam Hussein’s propaganda machine. The highly classified bomb created a brief pulse of microwaves powerful enough to fry computers, blind radar, silence radios, trigger crippling power outages and disable the electronic ignitions in vehicles and aircraft. Officially, the Pentagon does not acknowledge the weapon’s existence. Asked about it at a March 5 news conference at the Pentagon, Gen. Tommy Franks did not confirm this news (CBS News, 2003).

Carlo Kopp published the only open-literature studies about the e-bomb. In 1993, he defined a doctrine for the use of such devices, and then, in 1996, he introduced the technical and operational aspects of the e-bomb.

E-Bomb studies are heavily classified, and research surrounding them is highly secret. The nature of that information protection will affect the contents and analysis involved in this open source thesis effort.

B. DIRECTED ENERGY AND DIRECTED ENERGY WEAPONS (DEW)

1. Key Definitions

Directed Energy (DE): An umbrella term covering technologies that relate to the production of a beam of concentrated electromagnetic energy or atomic or subatomic particles (*Joint Publication 1-02, 161*) (Deveci, 2007).

Directed-Energy Warfare (DEW): Military action involving the use of directed-energy weapons, devices, and countermeasures to either cause direct damage or destruction of enemy equipment, facilities, and personnel, or to determine, exploit, reduce, or prevent hostile use of the electromagnetic spectrum through damage, destruction, and disruption. It also includes actions taken to protect friendly equipment, facilities, and personnel, as well as retain friendly use of the electromagnetic spectrum (*Joint Publication 1-02, 161*) (Deveci, 2007)

Directed-Energy Weapon: A system using directed energy primarily as a direct means to damage or destroy enemy equipment, facilities, and personnel (*Joint Publication 1-02, 162*) (Deveci, 2007).

The Electronic Warfare (EW) in the existing century is different from the traditional, old way of EW. In the new way, the defensive part of EW includes the offensive actions such as preventing the enemy's use of the electromagnetic spectrum through counter measures such as damaging, disrupting, or destructing the enemy's electromagnetic capability. DEW is considered to be as the representative of the new way of EW (Schleher, 1999).

2. Directed Energy Weapon Systems

Directed energy weapons include four types of weapons: high-energy lasers (HEL), charged particle beams (CPB), neutral particle beams (NPB), and High Power Microwaves (HPM). The most common characteristic of these weapons is that they attack at the speed-of-light. This helps in defeating targets such as theater and ballistic missiles before they can deploy defense-saturating sub-munitions. Another advantage of such weapons is that they can be used against multiple targets at the same time. Among all four weapon categories, HEL systems have the most potential for military technical revolution in order to be applied in both strategic defenses and tactical battlefield (Schleher, 1999). HPM technology, which will be base for the proposed e-bomb in this study, has similar potential also, but since it has not been as well funded and is accordingly less well developed, the technology for it seems behind that of lasers. On the other hand, particle beam weapons are still in the science fiction domain, as the weight and cost do not yet justify the weaponization (Kopp, 2006).

In this study, the e-bomb is defined as a kind of directed energy weapon. Even though the technical specifications of the e-bomb are based on the HPM technology, the means of e-bomb delivery differs from that of HPM. To understand the military utility of the e-bomb better and show the advantages and disadvantages of it, e-bomb will be assumed as the third electromagnetic weapon after HPM and High Altitude Electromagnetic Pulse (HEMP). The rationale is the similarities perceived between these technologies and the absence of any open-literature e-bomb data.

3. Directed Energy Weapon Concepts

Kopp has recently published an article about Directed Energy Weapons. In that article, he defines the Directed Energy Weapons basically as:

Directed Energy Weapons share the concept of delivering a large amount of stored energy from the weapon to the target, to produce structural and incendiary damage effects. The fundamental

difference is that a DEW delivers its effect at the speed of light, rather than supersonic or subsonic speeds typical of projectile weapons (Kopp, 2006).

DEWs have great potential for aircraft operations since crews can enhance their own survivability in the battlefield, where the aircrafts are susceptible and vulnerable to missile threats, by protecting themselves with electromagnetic shields. In such environment, DEW systems may prevent the aircraft from threats by decreasing the detection and targeting capability of enemy. They may also aid in hit avoidance by deflecting, blinding, or causing the incoming missile to break lock and finally, where necessary, to destroy the missile itself before it reaches its target. An additional approach might be to defeat the fusing system of the incoming missile (Schleher, 1999).

There are still two fundamental problems shared by Directed Energy Weapons. These problems are defined as “getting the projectile to successfully travel a useful distance and hit the target,” and then “produce useful damage effects” (Kopp, 2006).

C. ELECTROMAGNETIC WEAPONS

As mentioned above, three electromagnetic weapons will be defined in this study: High Altitude Electromagnetic Pulse (HEMP), High Power Microwave (HPM) Weapons, and Electromagnetic Bomb (e-bomb).

Even though e-bomb can be considered same as HPM weapons based on underlying technology, this study will assume that these two weapons are different due to means of delivery.

HEMP is not a directed energy weapon. The reason why HEMP is defined as an electromagnetic weapon is that it produces similar effects in electromagnetic spectrum and can cause similar impacts on electronic devices. In later sections, e-bomb utility will be evaluated in comparison with HPM and HEMP.

1. High Altitude Electromagnetic Pulse (HEMP)

High Altitude Electromagnetic Pulse (HEMP) is an instantaneous electromagnetic energy field produced in the upper atmosphere by the radiation of a nuclear detonation. The potential damage of HEMP on the electronic devices over a very wide area is dependent on the detonation altitude and the structural design of the nuclear device. As mentioned in the definition of the HEMP, a nuclear weapon detonated high above the Earth's surface is required to produce HEMP. In such way, the gamma-radiation is created that interacts with the atmosphere to create an instantaneous and intense electromagnetic energy field that does not damage the people as it radiates outward from the burst, but which can overload computer circuitry with effects similar to, but causing damage much more swiftly than a lightning strike (Wilson, 2006).

A test at the Pacific Ocean introduced the HEMP effects to the U.S. in 1962. The following observation was reported:

On July 8, 1962, at about 11:00 pm Hawaiian time, a nuclear detonation occurred 400 km above Johnston Atoll in the Pacific Ocean during a high-altitude nuclear test conducted by the U.S. under the code name "Starfish Prime." Approximately 800 miles from ground zero on the Hawaiian island of Oahu, 30 strings of street lights failed simultaneously at about the time of the Starfish shot" (Glasstone and Dolan, 1977).

After the explosion, Vittitoe who examined the Hawaiian street light incident, concluded that failure was caused by the electromagnetic pulse generated by the nuclear detonation. He concluded that *"Although the peak amplitude of the electromagnetic pulse was relatively small, the orientation of the street light circuits with respect to the incident electromagnetic pulse angle allowed a coherent buildup of surges which resulted in blown fuses"* (Vittitoe, 1988). When it is considered that the distance of the epicenter of the blasts is 800 miles from Honolulu, the 5.6 kV/m (kilovolts per meter) peak electric field estimated over Honolulu gives a good interpretation about how powerful HEMP can be (Longmire, 1985).

The HEMP effect can span thousands of miles, depending on the altitude as well as the design and yield of the nuclear burst (a single device detonated at an appropriate altitude over Kansas reportedly could affect all of the continental United States), HEMP can be picked up by metallic conductors such as wires or power cables, acting as antennas conducting the energy shockwave into the electronic systems of valued cars, airplanes, and communication (Wilson, 2006).

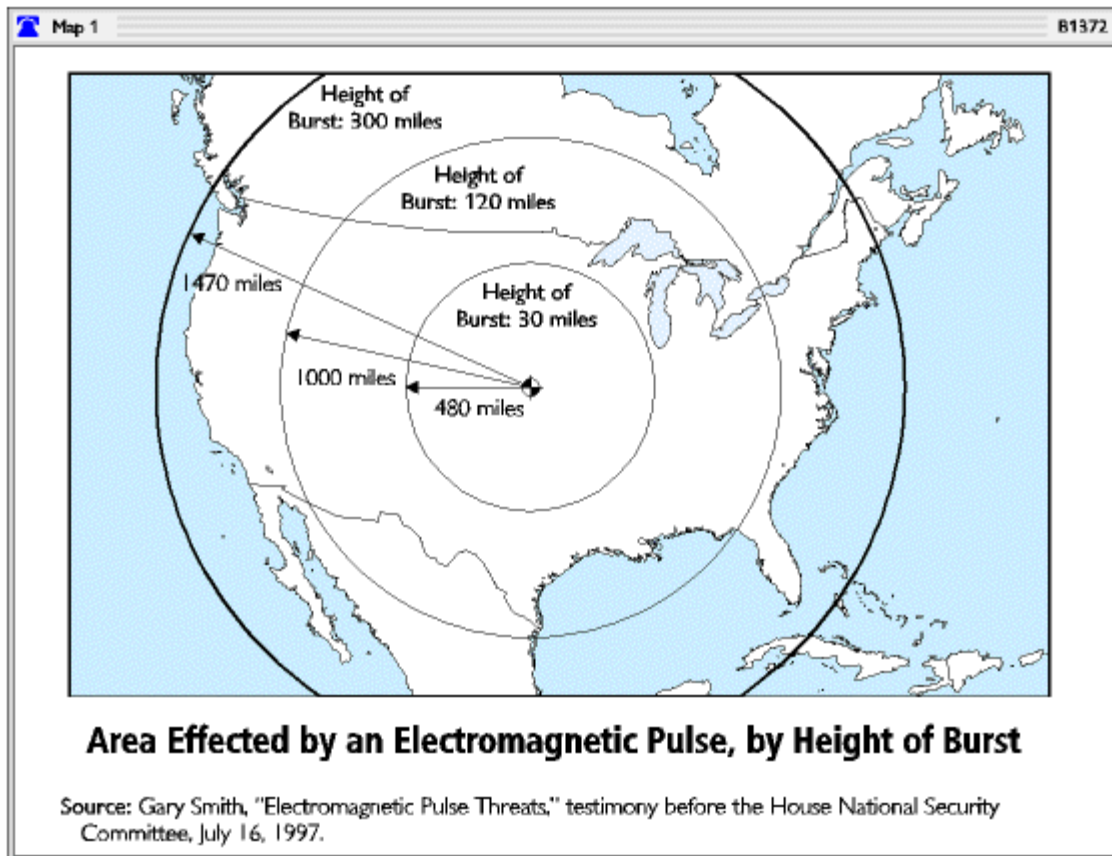


Figure 3. Estimated Area Affected by HEMP (Spencer, Heritage Foundation, 2000)

Since the electromagnetic pulse damage on unprotected electronic devices is limited by the blast's "line of sight," the altitude of the explosion determines the size of the affected area in harm's way. The higher the altitude, the greater the land area affected. Figure 3 shows the estimated affected area by such a HEMP. According to this figure, the HEMP produced by a single large nuclear weapon, detonated 125 miles (200 km) above the center of the

continental United States, would reach more than half of the country; a weapon detonated at 250 miles (400 km) would reach the entire country, though at lower pulse intensities.

Modern weapons with higher gamma-ray yields coupled with higher geomagnetic fields over the central U.S. could produce electromagnetic pulse with intense fields on the order of tens of kilovolts per meter (Kruse, Nickel, Taylor, Bonk and Barnes, 1991). For example, a one- or two-megaton device detonated at an altitude of 250 miles would reportedly produce a field strength of 10-50 kV/m, enough to produce extensive damage to electronics over the entire continental U.S. (Miller, 2005). Since HEMP is electromagnetic radiation traveling at the speed of light, the entire area could possibly be affected almost simultaneously. All communications, television, radio, cars, trucks, planes, etc., could be reached, resulting in an Electronic blanket where all electronics in the states could be affected (Spencer, Heritage Foundation).

Even though HEMP seems a major threat on electronic equipments, there are some challenges in generating such weapons. It is quite difficult and expensive, since it requires the ability to field both a nuclear weapon and a delivery system to get it to altitude. It must be noted that HEMP occurs for nuclear detonations above 25 miles and is most effective above approximately 70 miles. The higher the burst is, the more widespread the effect due to line of sight. Currently, the U.S., Russia, United Kingdom, France, China, India, Pakistan, and Israel have the capability to produce HEMP, and 11 other countries have similar potential, either due to indigenous weapons programs or arms trading (Miller, 2005).

2. High Power Microwave Weapons

High Power Microwave (HPM) is an imprecise term used by several communities studying generation of coherent electromagnetic radiation spanning the frequency range of 1 GHz to over 100 GHz. One interpretation of the term is high-average-power microwaves, which implies long-pulse duration, high

repetition rate or continuous beam source. Another interpretation is high-peak-power microwaves, which implies short-pulse duration, a low-repetition rate or “single-shot” source (Barker and Schamiloglu, 2001).

HPM in this thesis includes the features of HEMP and lightning. This is done intentionally to capitalize on the vast body of knowledge available for these two intense electromagnetic threats. Where necessary, the various electromagnetic threats will be contrasted to point out their inherent differences.

In various countries, High-power microwaves (HPM) operating in a single-shot or with tens or hundreds of Hz repetition rates are being developed. In addition to their frequency agility, they have been reached the power level at in the GW range (Giri, 2004). Since the power levels of HPM sources have been reached to GW levels, the application of HPM technology as a weapon for defense has been quite an interest for military purposes. It was realized that such applications may disrupt or even destroy the electronic systems of offensive weapons such as missiles (Giri, 2004).

Until the 1980s, various analysts working in HPM technology had considered using microwave radiation as a weapon as well as for communications and detection. Since damage thresholds levels of representative electronic devices were high when compared to available microwave output power (kilowatts) by that time, the use of HPM technology as a weapon was not in the interest of the analysts. Then, two new technological advents changed this belief. First, the source development of microwave power in the Gigawatt range posed a plausible threat to military equipment. Second, the military grew increasingly dependent on microelectronics that were susceptible to large voltage transients at much lower power levels than their predecessors. These two developments made analysts begin to believe that along with the rapid advance of pulsed power technology, HPM might play an important role for the battlefield of the future. These devices might have a use in traditional Electronic Warfare (EW) missions. They can be used as a jammer against the enemy radar, and command and control systems. But this is not all they might accomplish. They

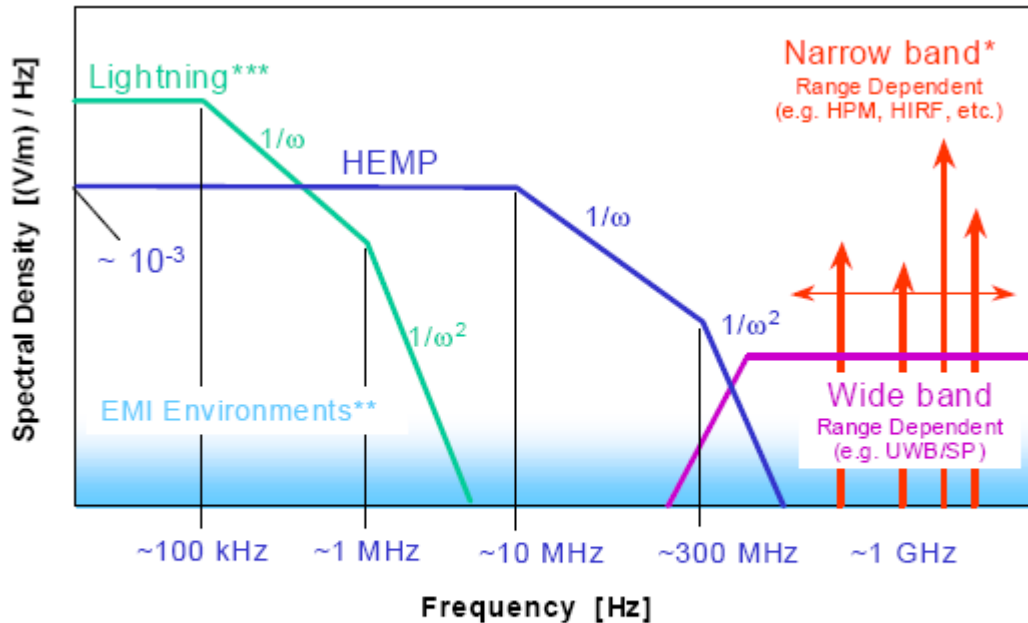
might also disable or disrupt the enemy aircraft and missiles in the air or on the ground. This utility provides a wide variety of offensive and defensive missions. HPM uses could range from air base defense, aircraft self-protection, and suppression of enemy air defenses, attacks on airfields, imprecisely located or “strategic relocatable” targets (mobile missiles and command posts), and satellites (Barker and Schamiloglu, 2001).

The potential effects of a designed HPM weapon strongly depends on the electromagnetic properties of the target. Since it is difficult to get the required intelligence, the complexity of real systems poses technical difficulties (Giri, 2004).

The recent comparison of HEMP and HPM resulted in a published report. The spectra of the Source Region electromagnetic pulse and of the lightning are shown on Figure 4. The following conclusion was made:

The low level electromagnetic signals covering the whole spectrum represent the various electromagnetic interferences due to all kind of sources and which are the most common electromagnetic environment today. It can be seen that the HEMP and HPM present a similar shape, but that:

- the frequency of 300 MHz represents the maximum significant value for HEMP, but it is the minimum value for HPM;
- the amplitude of the HEMP signal is about one order of magnitude higher than the signal produced by an HPM source” (Ianoz, 2008).



Notes: * narrow band extending from ~ 0.5 to 3 GHz
 ** EM noise environments, not necessarily HPEM
 *** significant spectral components up to ~ 20 MHz, depending on range

HIRF : High Intensity Radiated Field

UWP/SP : Ultra Wide-Band/Short Pulse

EMI Environments : Electromagnetic Interference Environments

HPEM : Emerging High Power Electromagnetic

Figure 4. Comparison of the Spectral Density of Several Types of EM Environments (Giri and Tesche, 2004)

A typical HPM weapon system basically includes a prime source that generates the intended power, an RF generator, a system that shapes and forms the wave into the intended form, a waveguide through which the generated wave travel, an antenna that propagated the wave, and the control unit that manages all the steps (see Figure 5).

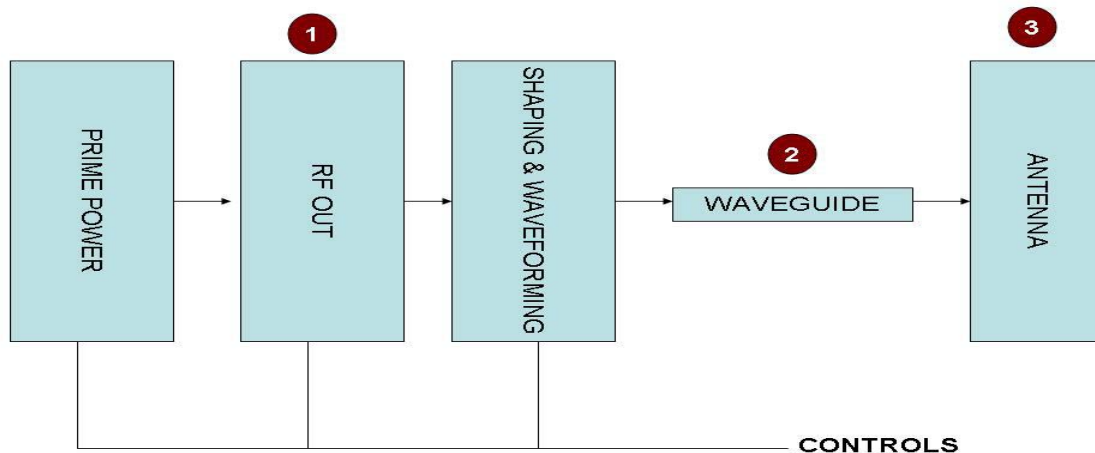


Figure 5. HPM Weapon System

For this study, the following three items are considered the basic elements used to explain the theory for HPM weapon systems:

- HPM power supply
- Waveguide
- Antenna/reflector

Each of these parts limits the design in some way and affects the other parts.

a. HPM Power Supply

The operating principles of various microwave sources are presented in this section.

(1) Klystron. The klystron is a high-frequency oscillator and amplifier that was invented in the late 1930s by R. H. Varian and S. F. Varian. The output capabilities of modern klystron tubes are steadily being improved. In general, klystrons provides high pulse and continuous wave (CW) power with medium bandwidth limitations. Relatively high gains (up to 70 dB) and

efficiencies (up to 70%) can be achieved. Efficiency refers to what fraction of the input DC power for CW sources is converted into microwave power (Taylor and Giri, 1994).

(2) Magnetrons. The magnetron is a self-contained microwave oscillator that operates differently from the linear-beam tubes, such as the klystron. crossed-electron and magnetic fields are used in the magnetron to produce the high-power output required in radar and communications equipment (Buczynski, 2003). The magnetron tube was perfected before the klystron and is the more widely used device for power oscillator applications. In the late 1970s, 100-MW pulsed magnetrons and klystrons became commercially available. However, a relativistic magnetron source in the L band producing 1.8 GW of peak power is now commercially available (Taylor and Giri, 1994).

(3) Gyrotrons. The gyrotron is a new type of microwave device that operates at millimeter wavelengths. For these devices, the electron beam is normally a thin hollow cylinder configuration and is directed into a strong axial magnetic field inside a circular cylindrical cavity. Some reported output powers from gyrotron oscillators under pulse operation are 800 MW at 7.5 GHz, 350 MW at 15 GHz, and 8 MW at 37.5 GHz (Taylor and Giri, 1994).

(4) Vircators. The virtual cathode oscillator, or vircator, is a high-power source capable of operation within the frequency range of a few hundred megahertz to tens of gigahertz. Very high outputs (up to 20 GW) have been reported for the vircator. Pulse lengths of ten to several hundred nanoseconds can be produced. Usually the pulse length is controlled by the electrical pulse driving the anode, although other factors are involved (Taylor and Giri, 1994).

Vircator is the most appropriate device among all other HPM sources in terms of use in munition applications. Since it is simple in design, relatively cheap in production and capable of generating tens of Gigawatts of power, these features attract significant interest of electromagnetic weapon world (Kopp, 1996).

Figure 6 shows an axial virtual cathode oscillator defined by Kopp. The detailed information about the vircator can be found in open literature and is beyond the purpose of this study.

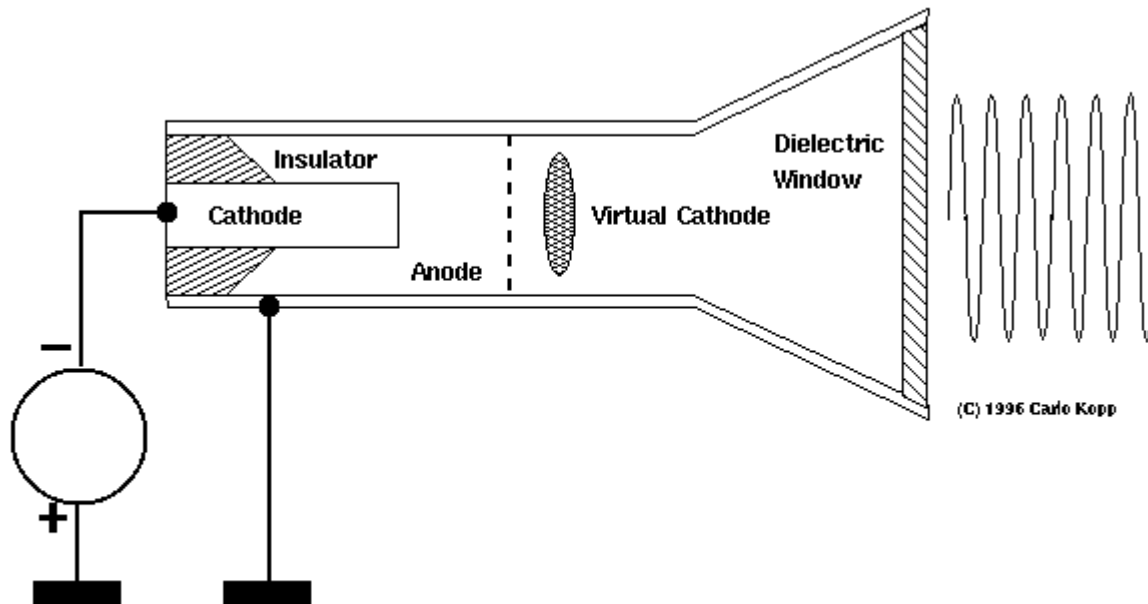


FIG.3 AXIAL VIRTUAL CATHODE OSCILLATOR

Figure 6. Vircator (Kopp, 1996)

(5) Ubitron/Free-Electron Lasers. The ubitron is a device that uses an electron beam directed past a set of periodically spaced magnets where the electron velocities are near the speed of light. Output power levels exceeding 1 GW have been reported (Taylor and Giri, 1994).

(6) Klystronlike Intense Relativistic Electron Beam Devices. Generally, these devices have a low efficiency. The so-called intense relativistic electron beam device incorporates a converter to achieve high efficiencies in the conversion of electron kinetic energy into electrical energy. Recent simulation studies have been performed on the design of such devices.

The simulation results show that for a very large diameter (26 cm) intense beam (466 keV, 100 kA), it appears that 31 GW of RF beam power can be developed at 1.3 GHz (Taylor and Giri, 1994).

In order to be considered a viable source for a high-power microwave weapon, a device should provide an output power that exceeds 1 GW (Benford, 1987). A comparison of the outputs from these devices is shown in Figure 7. It can be seen that a vircator can be the best performing power source for 1 GHz frequency, where a magnetron has better performance for 3 GHz. According to desired frequency level, other power sources can be considered as an alternative to the best performing sources.

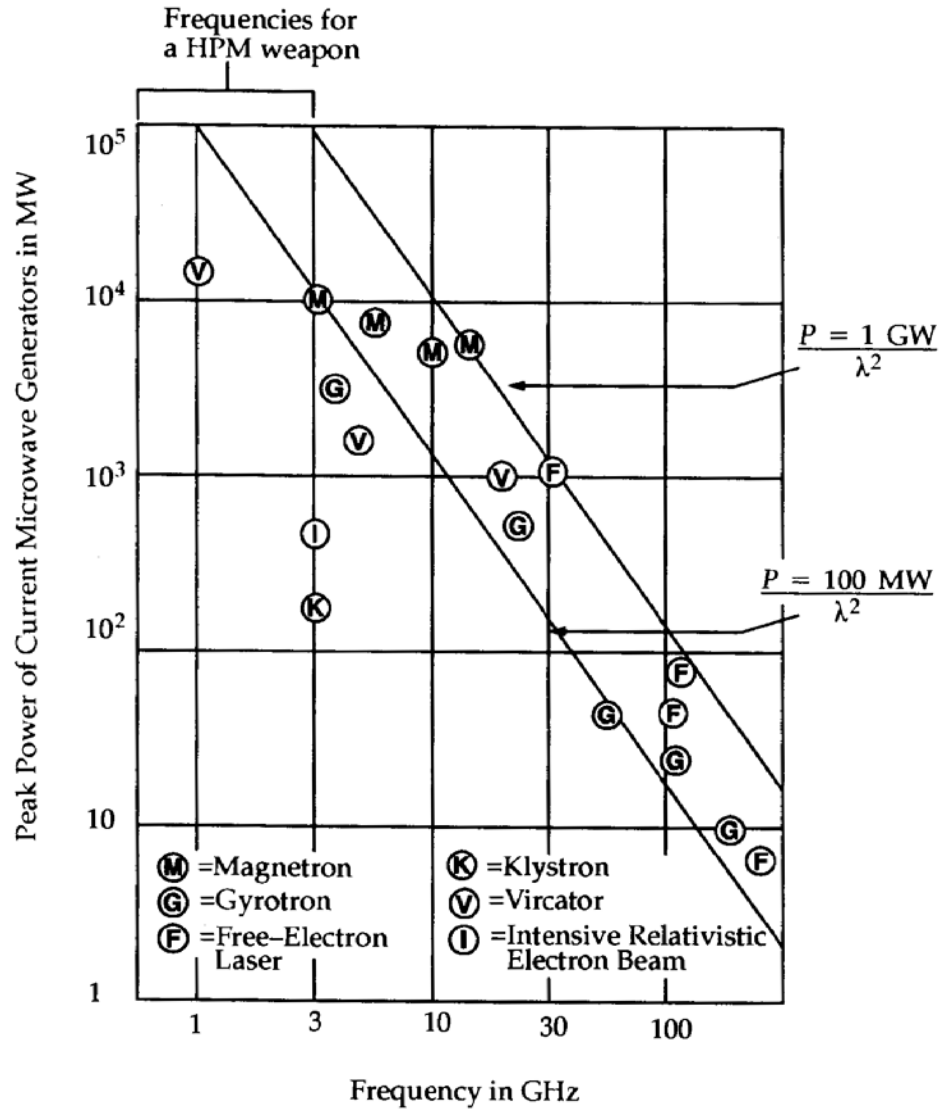


Figure 7. Comparison of Device Peak-Power Generation (Taylor and Giri, 1994)

b. Waveguide

Waveguides are metallic transmission lines that act as a duct for propagating microwave radiation typically to interconnect transmitters/receivers with antennas. They also act as a radiating element without an antenna for electromagnetic waves at microwave frequencies (i.e., open-ended waveguide).

In this study, every design of electromagnetic weapon will include only rectangular waveguides. There are two independent classes of waveguides: Transfer Magnetic (TM) modes and Transverse Electric (TE) modes.

A conducting waveguide operating in the lowest-order transverse electric (TE) mode is often used in transitioning a sinusoidal electromagnetic wave from source to radiating antenna. Extending this concept to pyramidal horns, waves can be launched from one or more waveguide/sources (Taylor and Giri, 1994).

The most important problem of waveguide use in HPM weapons is the maximum field strength that a waveguide filled with air can propagate (around 3 MV/m). However, a proven method is used to overcome this problem. That is vacuuming the waveguide and filling with appropriate gas. If the waveguide is operated under high-vacuum conditions, it can propagate very large electric fields. In order to bring the power out of the waveguide, the fields need to be reduced below the dielectric strength of the ambient medium (air or some high-dielectric-strength gas such as SF₆ at 1 atm) (Taylor and Giri, 1994).

Band Design	Range (GHz)	Internal (inches)	Internal (mm.)	Official Designations		
				I.E.C.*	U.K. (RCSC)	U.S. (EIA)**
	0.96 - 1.45	7.7 x 3.85	195.58 x 97.79	R12	WG5	WR770
	1.12 - 1.7	6.5 x 3.25	165.10 x 82.55	R14	WG6	WR650
	1.45 - 2.2	5.1 x 2.55	129.54 x 64.77	R18	WG7	WR510
	1.7 – 2.6	4.3 x 2.15	109.22 x 54.61	R22	WG8	WR430
	2.2 – 3.3	3.4 x 1.7	86.36 x 43.18	R26	WG9A	WR340

*IEC : International Electrotechnical Commission

**EIA : Electronic Industry Association

Table 1. Rectangular Waveguide Specifications (Microwave Encyclopedia, Microwaves101.com [08/12/2008] abstracted from <http://www.microwaves101.com/content/downloads.cfm>)

Table 1 shows the waveguide dimensions and designations for the interested frequencies. This table will be the main source to decide what kind of waveguide will be used in design of e-bomb in later chapters. More detailed waveguide features are listed in Appendix A.

c. Antenna/Reflector

A traditional way of illuminating a reflector horn for a narrow band CW signal is by a pyramidal horn. The pyramidal horn and the reflector have to work in conjunction to produce the desired radiation patterns (Giri, 2004). Another way to propagate the wave is to use a parabolic dish antenna. In later chapters, the e-bomb model will include either the pyramidal horn antenna or a parabolic dish antenna.

3. Electromagnetic Bomb (E-Bomb)

An electronic bomb, or e-bomb, is a form of directed energy with potential military applications. In this study, HPM basic transmission theory is used to define the characteristic of hypothetical e-bomb.

The use of HPM warheads on precision guided munitions is an attractive coupling of electronic attacks with precision guided munitions (PGMs) and includes such platforms as accurate missiles, glidebombs, and unmanned aerial vehicles (UAVs). Carlo Kopp, who coined the term E-bomb in 1995, when the U.S Air Force originally published his work, envisioned combining a smart bomb with a HPM warhead (Benford, Swegle and Schamiloglu, 2007).

Kopp in his article mentions about the electromagnetic pulse as “an electromagnetic shock wave.” This pulse produces a powerful electromagnetic field, particularly within the vicinity of the weapon burst that can be sufficiently strong to produce short duration transient voltages of several of kilo volts on exposed electrical devices that include conductors, wires, or conductive tracks on printed circuit boards (Kopp, 1993).

He also defined the Flux Compression Generators (FCGs) and HPM devices, especially vircator, as the key technologies which may be used in e-bomb technology (Kopp, 1996). HPM devices (and vircators) are mentioned previously in this report as special systems offering unique performance (frequency, amplitude, power) features. These devices are not commonly available. On the other hand, FCG is defined in the open literature as a mature technology. FCGs can produce peak electrical energies of megajoules in tens to hundreds of microseconds. These performance attributes make FCG technology appealing for e-bomb consideration at high frequencies. The biggest advantage with respect to usage for e-bomb is that the FCGs can be compact and generate power in TerraWatts or tens of TerraWatts (Kopp, 1996). As designed by Kopp, Figure 8 shows the detailed technical parts and the discharge picture versus time for helical FCG.

Since the effectiveness of the flux generator is limited because of the coupling efficiency of a low frequency pulse, and low-frequency pulses are important, the vircator appears to be a better approach to designing an e-bomb (Kopp, 1996).

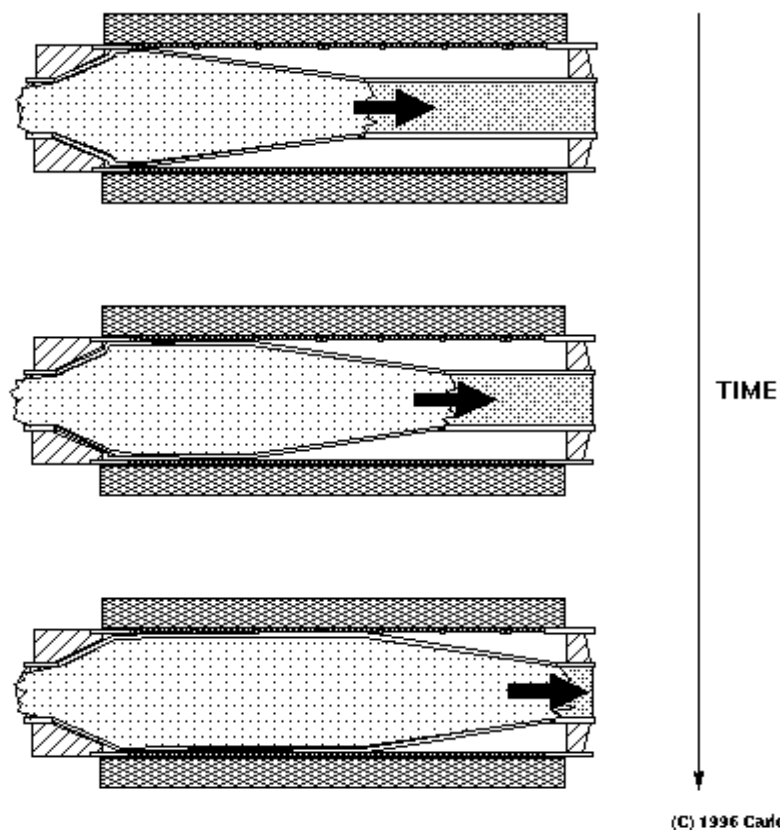
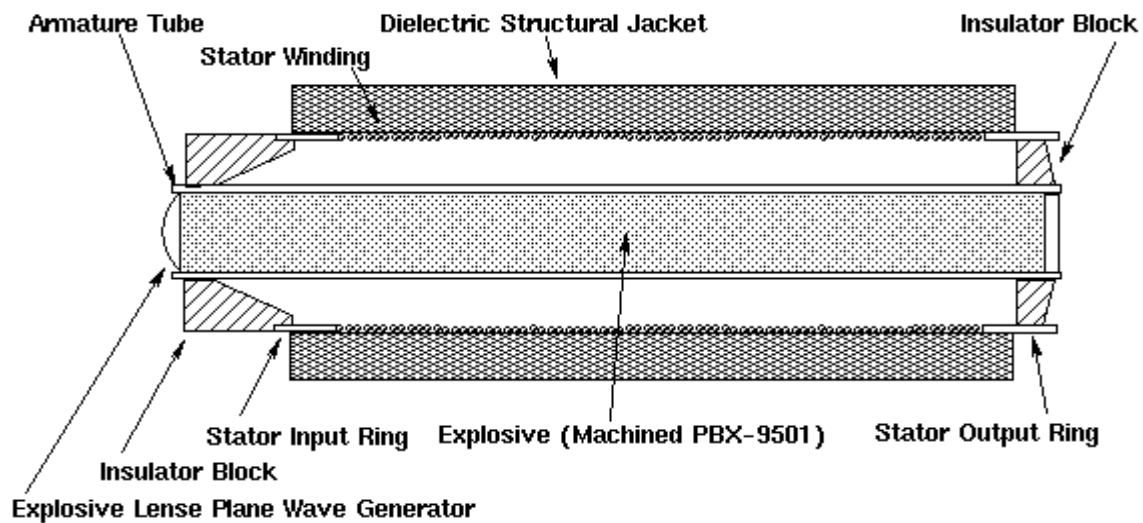


FIG.2 EXPLOSIVELY PUMPED COAXIAL FLUX COMPRESSION GENERATOR

Figure 8. Flux Compression Generator (Kopp, 1996)

A vircator/antenna combination defined by Kopp is shown in Figure 9. Especially a circularly polarized wideband antenna application in an e-bomb design would require a tapered helix or conical spiral antenna in order to provide a better application for large power with minimal losses.

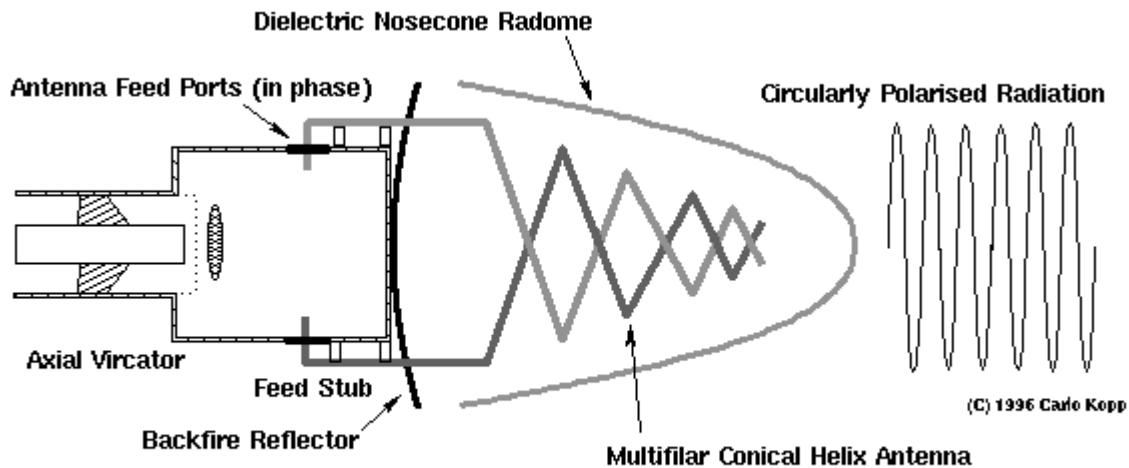


FIG.5.2 EXAMPLE OF VIRCATOR/ANTENNA ASSEMBLY

Figure 9. Vircator/Antenna Combination (Kopp, 1996)

An e-bomb design will include consideration about the delivery system options available. The weapon may dictate the delivery system, or alternatively the delivery system constraints may heavily influence the e-bomb design. Delivery system considerations are very important.

The massed application of such electromagnetic weapons in the opening phase of an electronic battle delivered at the proper instant or location can quickly lead the superiority in the electromagnetic spectrum. This package might mean a major shift from physically lethal weaponry to electronically lethal attacks (via e-bombs) as a preferred mode of operation. Potential platforms for such weapons delivery systems are the U.S. Air Force-deployed global positioning system (GPS) aided munition on the B-2 bomber and the GPS/internally guided GBU-29/30 JDAM (Joint Direct Attack Munition) and the AGM-154 JSOW (Joint Stand Off Weapon) glidebomb. The attractiveness of glidebombs delivering HPM warheads is that the weapon can be released from outside the effective radius of

target air defenses, minimizing the risk to the launch aircraft, which can stay clear of the bomb's electromagnetic effects (Benford, Swegle and Schamiloglu, 2007).

Kopp proposed two delivery methods, both include the Mk.84 warhead delivery form (shown in Figure 10 and 11). GPS guided bombs and AGW glidebombs are intended to be used by this type of delivery. One of the Mk.84 designs that he proposed includes a pure helical FCG and coaxial short circuit load. His second design concept includes a vircator tube feeding a conical horn for the second stage of the bomb. Both designs can be seen in Figure 10 and Figure 11 respectively.

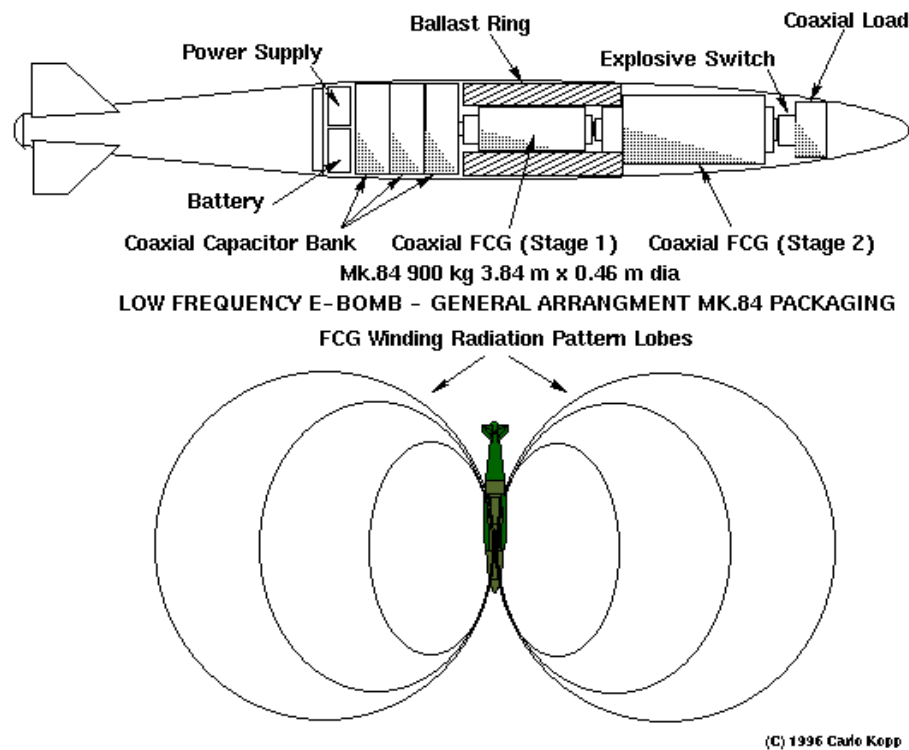
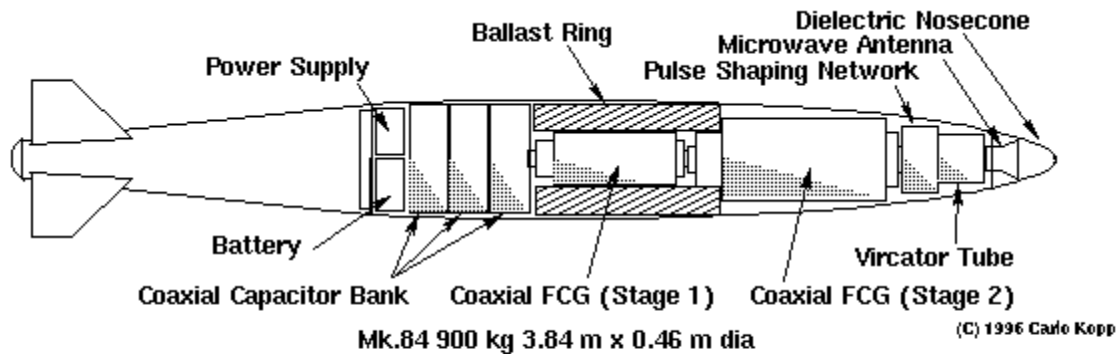


FIG.4 LOW FREQUENCY E-BOMB WARHEAD (MK.84 FORM FACTOR)

Figure 10. MK.84 E-Bomb Warhead (Kopp, 1996)



**HIGH POWER MICROWAVE E-BOMB - GENERAL ARRANGMENT MK.84 PACKAGING
WARHEAD USING VIRCATOR AND 2 STAGE FLUX COMPRESSION GENERATOR**

FIG.6 HPM E-BOMB WARHEAD (Mk.84 FORM FACTOR)

Figure 11. MK.84 HPM E-Bomb Warhead (Kopp, 1996)

Another delivery method of e-bomb may be the use of UAVs. The technology of UAVs is still developing and partly immature; however, improvements can be expected in the next decade.

The e-bomb targets mission essential electronic systems such as the computers used in data processing systems, communications systems, displays, industrial control applications, including road and rail signaling, and those embedded in military equipment, such as signal processors, electronic flight controls and digital engine control systems (Kopp, 1996).

When e-bomb outputs are too weak to destroy these systems but strong enough to disrupt their operations, system performance can be degraded. On the other hand, and when intense fields are involved, these targeted electronic devices and electrical equipment may also be destroyed by the electromagnetic pulse effect. Since new technology diodes, integrated circuits, transistors, and microprocessors are getting more and more vulnerable and sensitive to electromagnetic transients, any device that includes these devices can be potential target for e-bombs. This study will also attempt to assess whether an e-bomb could, potentially, be a major threat against complex systems such as commercial airplanes, military aircraft, or other military systems.

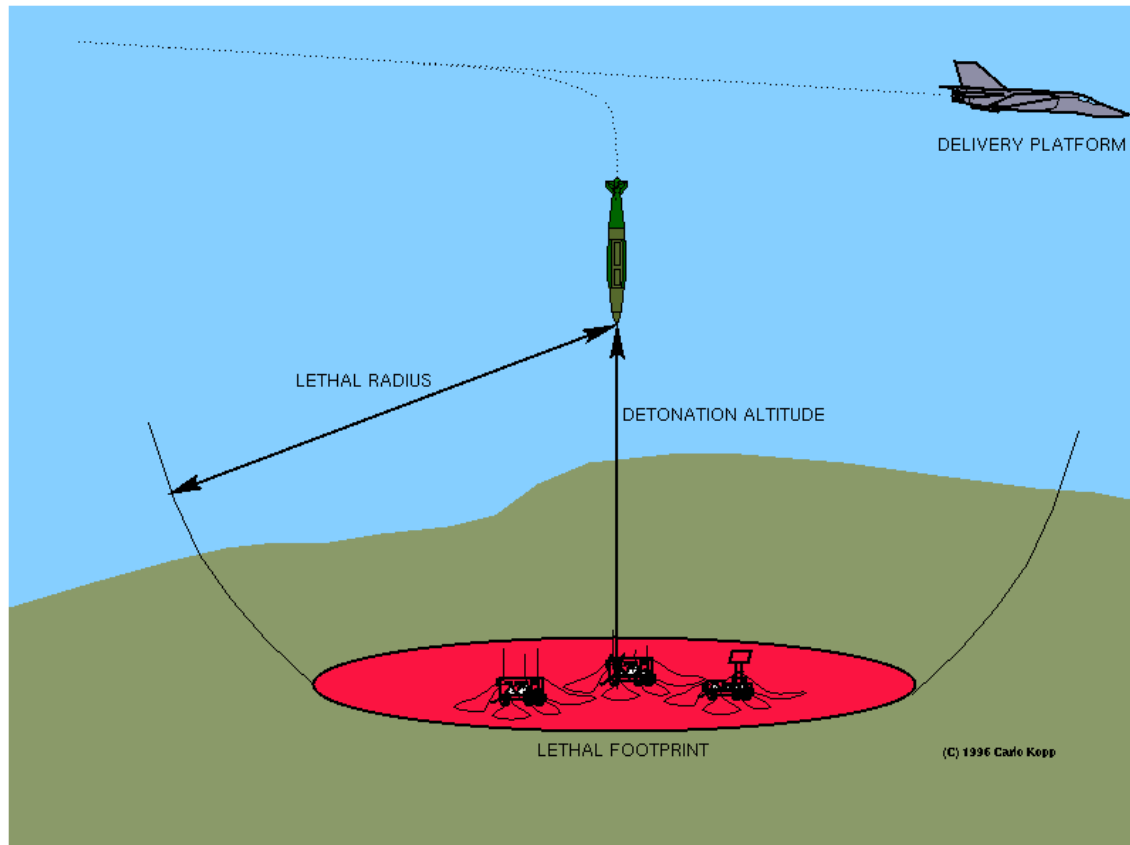


FIG.7 LETHAL FOOTPRINT OF LOW FREQUENCY E- BOMB IN RELATION TO ALTITUDE

Figure 12. An e-bomb delivery method (Kopp, 1996)

Figure 12 shows the relation between the altitude where the e-bomb is detonated and a representation of the lethality range. Target information (to include location and vulnerability) becomes an important issue. If the lethality range for the specific target is estimated, the optimum detonation altitude for a known device yield can be calculated in order to provide the maximum lethality footprint as shown. If the target systems are located in relatively narrow area like in Figure 13, a higher detonation altitude can be implemented while still covering the entire footprint, while keeping the delivery platform well out of the stand-off range. All these parameters must be considered in deciding on detonation altitude.

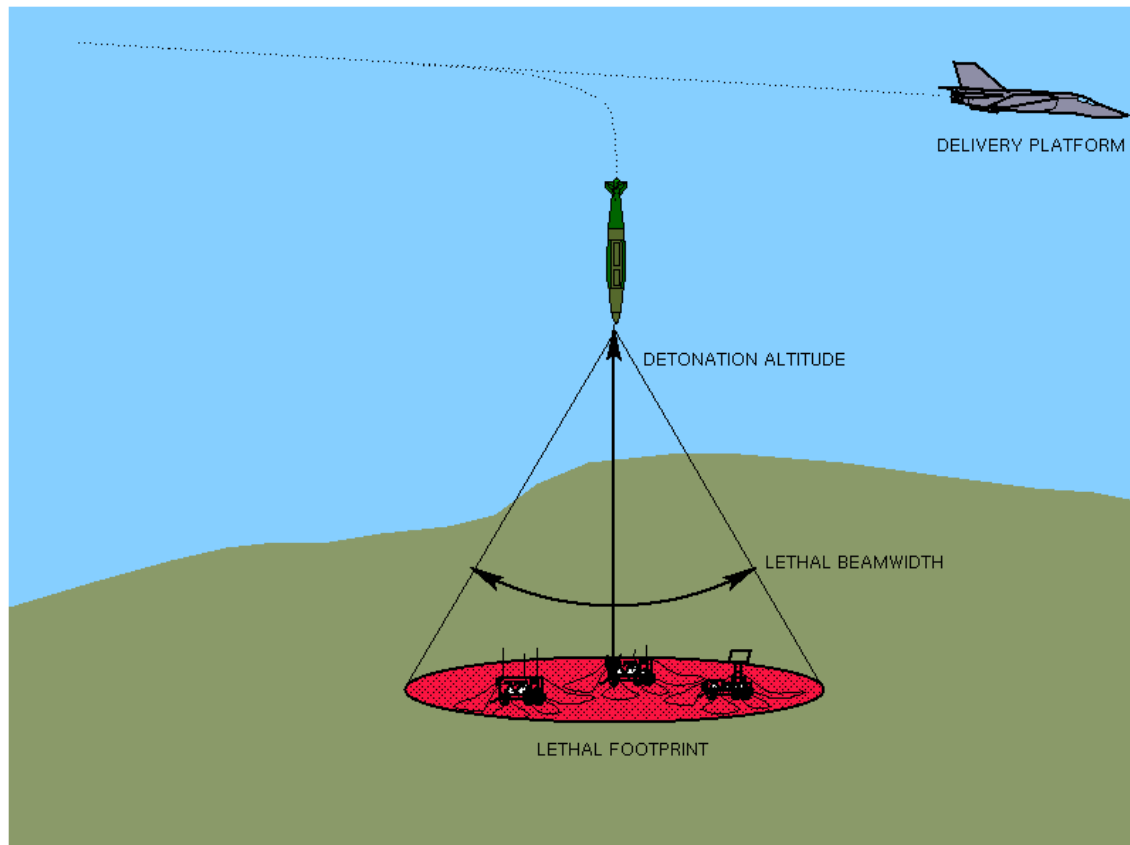


FIG.8 LETHAL FOOTPRINT OF A HPM E-BOMB IN RELATION TO ALTITUDE

Figure 13. Delivery method of e-bomb (Kopp, 1996)

A significant problem with the delivery of e-bomb as either “guided” or “dumb” bombs is required accuracy. A GPS aided bomb uses a smart tailkit equipped with an internal navigation package and a GPS receiver, which provide such weapons with a circular error probably between 6 and 12 meters. Such weapons are fully autonomous, all-weather capable, and employ intelligent guidance algorithms, which allow the weapon to engage the target with a preprogrammed trajectory (Kopp, 1996). Dumb bombs, on the other hand, have a great deal of inaccuracy involved in their delivery.

Because of the simplicity of the e-bomb in comparison to weapons such as Anti Radiation Missiles (ARMs), it is not unreasonable to expect that they should be cheaper to manufacture and easier to support in the field, thus allowing for more substantial weapon stocks (Kopp, 1993).

III. HYPOTHETICAL ELECTROMAGNETIC BOMB

Directed energy is not a science fiction. These are real weapons being tested in real scenarios... And those nations that are not prepared to exploit directed energy will stagnate or even worse, lose, by clinging to outmoded traditional forms of warfare. They will fall behind, just as civilizations that clung to the bow and arrow lost to the rifle and just as bullets and bombs will fall to DEW...(Beason, 2005)

— Doug BEASON, PhD

In this chapter, HPM theory and the general design principles introduced in the previous chapter are to define a notional e-bomb. Our e-bomb includes an HPM power source, appropriate waveguide, and an antenna/reflector. The pulse generated by the HPM source follows a rectangular wave shape.

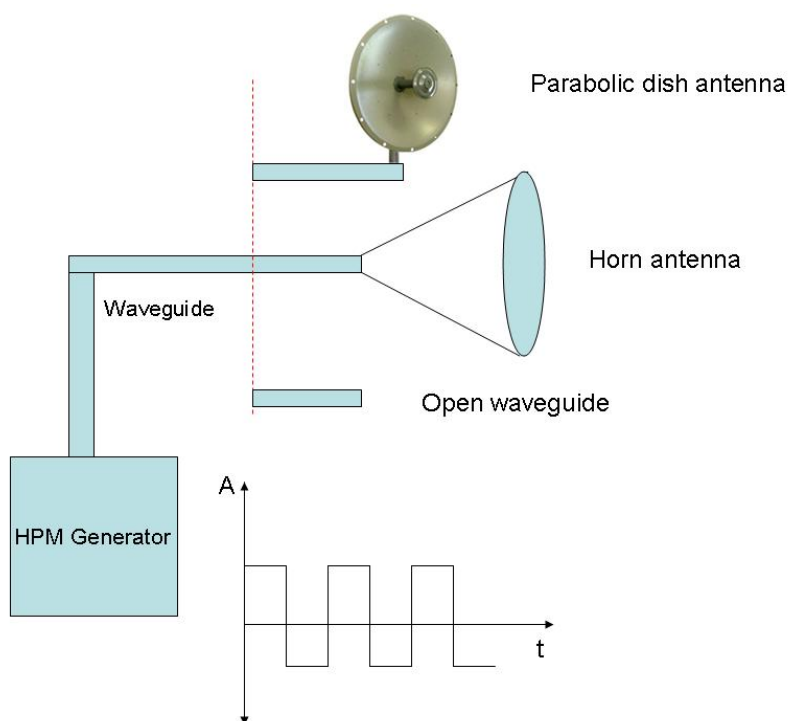


Figure 14. E-Bomb major elements

First, the theory behind HPM technology is defined. Next, the device radiated output is described and used to define the propagation pattern of generated electromagnetic field to ill be estimated as a function of range. Then, the coupling mechanisms between the HPM device output and the target system are defined. After defining the yield for the conception e-bomb from an HPM source, the impact on electronic systems is considered. The basis for consideration is according to the known, published threshold values of electronic systems. The possible effects are analyzed and the potential lethality range for different targets is estimated. A flow diagram of the described process is shown in Figure 15.

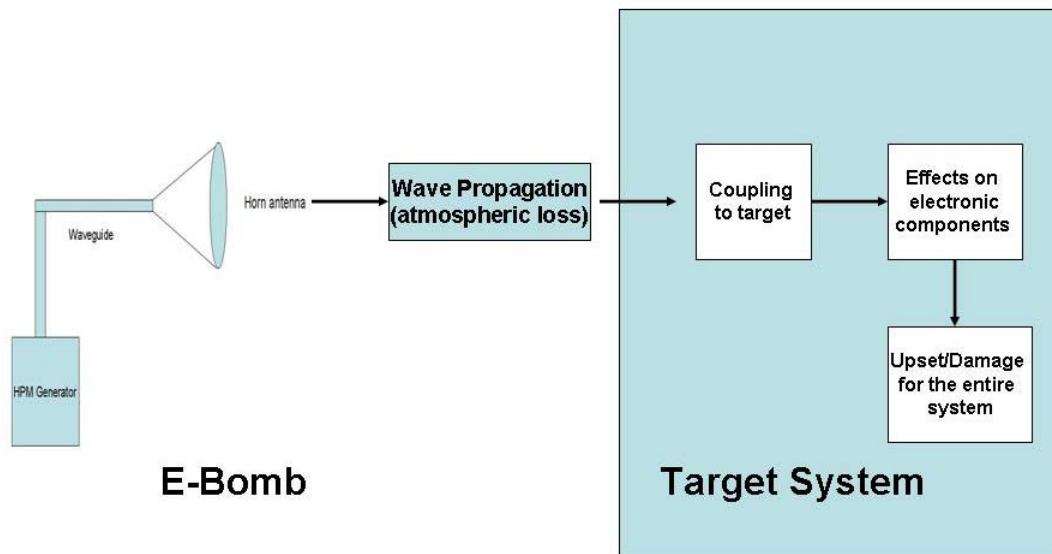


Figure 15. The e-bomb microwave flow from the power source to the damage/upset of target system.

To support the interaction assessment, a MATLAB model is used to simulate e-bomb effects using HPM theory. Published data for relevant systems is then used to validate the model.

Finally, defense against e-bomb are considered, and the advantages/disadvantages of different types of e-bomb design features are evaluated in terms of the military utility.

A. NOTIONAL PHYSICAL PRINCIPLES

1. Specifications

For our model, a frequency range between 0.5 GHz and 3 GHz is used. The reason to choose this range is that the ultrahigh frequency (UHF) region from 300 MHz to 3 GHz is extensively populated with radars, television broadcasting and mobile communications involving aircraft and surface vehicles. For most military operations environments, collateral effects on important use civilian systems is unacceptable, and should be avoided.

According to the described frequency range, an appropriate rectangular waveguide is chosen from Table 1. If there is more than one appropriate waveguide for the specified frequency range, the one with greater dimensions in size is used, since it provides a better field strength in far field. It also provides relatively lower field strength in the waveguide, which avoids the field strength exceeding the atmospheric breakdown limit (leading to ionization instead of propagation).

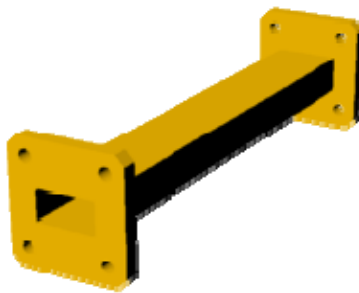


Figure 16. Rectangular waveguide

For the simulation model, the frequency (f) and the duration of the microwave pulse/pulsewidth (τ) will be decided by the user. For the purpose of this study, 100 nanoseconds (ns) is chosen as the default pulsewidth to make relevant but meaningful comparison between the different classes of e-bomb. For frequencies at or above 1 GHz frequency, 100 ns pulsewidth will contain 100 cycles and from an interaction viewpoint, 100 cycles should be adequate to ring up most system resonances, resulting in a steady-state maximum signal (voltage or current) at the failure port (Taylor and Giri, 1994).

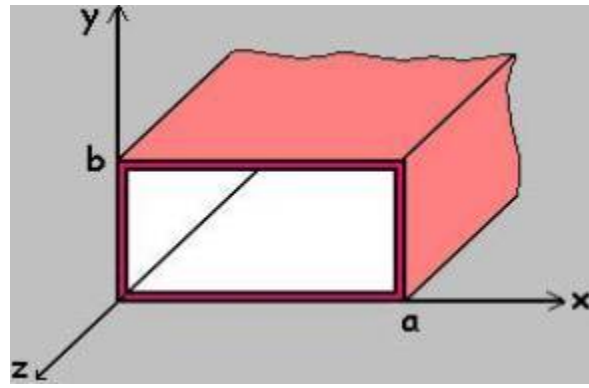


Figure 17. Waveguide dimensions

As seen on Figure 17, let the inner dimensions of the waveguide be :

a: larger dimension of the waveguide

b: smaller dimension of the waveguide.

Since $a > b$, the TE_{10} mode has the lowest cutoff frequency, it is generally desirable to have only one propagating mode in the waveguide. This minimizes dispersion and allows more efficient operation of the waveguide (Taylor and Giri, 1994).

The model impedance for the rectangular waveguide that operates in TE_{10} mode is

$$Z_{1,0} = Z_0 \left[1 - \left(\frac{\lambda}{2a} \right)^2 \right]^{-1/2} \quad (1)$$

where

- Z_0 : wave impedance of free space ($\mu / \varepsilon = 120\pi$)
- λ : operating wavelength ($\lambda = \frac{c}{f}$, where the c is the speed of light in free space, 3×10^8 m/s)
- a : larger dimension of the waveguide (Taylor and Giri, 1994).

For our e-bomb simulation, the dimensions of the waveguide are entered by the user. Free space wave impedance will be reference impedance in the simulation as shown in equation (1).

Once the model impedance is determined, the peak electric field (E-field) in the waveguide is given by:

$$E_{\max}(\text{waveguide}) = \sqrt{\frac{4}{ab} Z_{1,0} P_{\text{avg}}} \quad (2)$$

where

- $Z_{1,0}$: model impedance of waveguide
- P_{avg} : average power of HPM source
- a : larger dimension of the waveguide
- b : smaller dimension of the waveguide (Taylor and Giri, 1994) (Giri and Tesche, 2003) (Giri, 2004).

For the simulation, the average power will be entered by the user in terms of the classifications of e-bomb, which will be defined later in this chapter.

Another issue for HPM propagation is the atmospheric breakdown limitations. The upper limit of microwave power that can be transmitted in a waveguide and in the air is determined by the dielectric strength of the medium in which the microwave pulse propagates. As a rule of thumb, 3 MV/m maximum

field strength is assumed the maximum field strength that the atmosphere can propagate. The upper limit of the breakdown field strength depends on the pulsewidth. A simplified expression for the critical electric field strength, E_{bd} [V/m], for dielectric breakdown of a microwave pulse in air at atmospheric conditions is given by (Larsson, Johansson, and Nyholm, 2006)

$$E_{bd} = 22.5p \left[1 + \frac{42 \times 10^{-3}}{p\tau} \right]^{3/16} \quad (3)$$

where

p : ambient pressure in pascals

τ : pulsewidth of microwave.

Obviously, if the pulsewidth is increased, the breakdown field strength will decrease. In the e-bomb simulation, 1013.25 hectopascal (hPa) will be used since it is the average atmospheric pressure at sea level on the earth (see Figure 18 which shows the breakdown field strength as a function of air pressure for different pulsewidths).

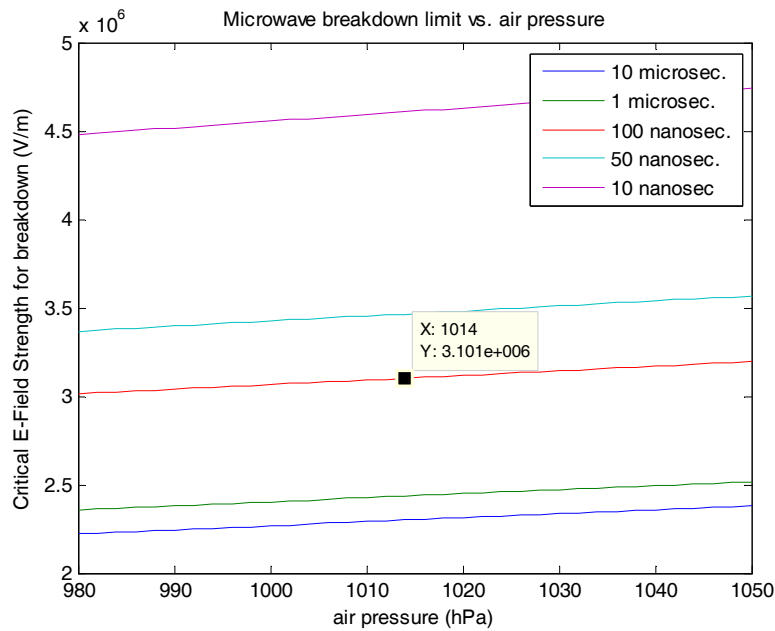


Figure 18. The critical electric field strength for different pulsewidths

For the standard atmospheric conditions (1013.25 hPa), the maximum field strength that can propagate in the atmosphere is around 3.10 MV/m for 100 ns. pulsewidth (the standard pulsewidth for the simulation).

The breakdown limitation formula shown in equation (3) is valid for air only. The waveguide may be filled with different inert gas, for example sulphur hexafluoride (SF₆), which has a critical field strength level of 3-4 times that of air at microwave frequencies (Larsson, Johansson, and Nyholm, 2006). Combinations of SF₆ and Nitrogen (N₂) have also proved valuable when working with pulse power technology at peak output.

If the waveguide is vacuumed and then filled with appropriate gas with a high dielectric strength, a field strength up to 74 MV/m can be sustained in the waveguide (Taylor and Giri, 1994).

As mentioned before, in HPM applications at GW power range, the waveguide and the horn are evacuated. But the dimensions of the horn aperture must have a minimum value at which the power density and the peak electric field at the aperture of the antenna enable the transition from the vacuum to 1 atm. SF₆ gas. This means that the peak electric field at the aperture of the antenna must also be below the breakdown electric field. For the simulation, this value is around 3.10 MV/m. As seen on Figure 19, if the aperture has dimensions a' (width of the aperture, larger dimension) and b' (height, smaller dimension), corresponding to the a and b of the waveguide, the peak electric field at the aperture is estimated by

$$E_{peak} (at the aperture) = E_{bd} = E_{max} (waveguide) \times \sqrt{\frac{ab}{a'b'}} \quad (4)$$

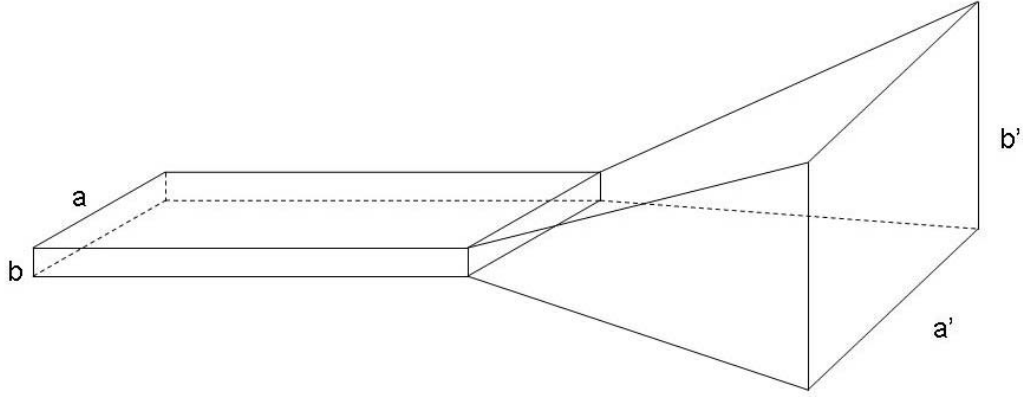


Figure 19. Aperture details of the proposed horn antenna

If it is assumed that $\frac{a}{a'} = \frac{b}{b'}$, the equation (4) becomes

$$E_{peak} \text{ (at the aperture)} = E_{bd} = E_{max} \text{ (waveguide)} \times \left(\frac{b}{b'} \right) \quad (5)$$

Once the minimum value for b' is calculated, other dimension of the horn, a' , can be calculated as well (Taylor and Giri, 1994) (Giri, 2004).

For example, at $f = 1.2$ GHz and $P_{avg} = 2$ GW, the peak electric field in the waveguide is found to be 14.3 MV/m, which means that $\frac{b}{b'}$ should be about 0.2165 in order to keep the electric field below 3.10 MV/m at the aperture of the horn antenna. As a result, the minimum dimension of b' is $(97.79 \text{ mm}/0.2165) = 45.17 \text{ cm}$. Using the same ratio for a' , it is found to be that a' is $(195.58 \text{ mm}/0.22) = 90.33 \text{ cm}$.

The other option can be the use of parabolic dish (see Figure 20) instead of horn antenna. If the focal length of the parabolic dish (F) is known, the peak electric field at the aperture can be estimated without using the dimensions of the antenna by

$$E_{peak} (at the aperture) = E_{max} (waveguide) \frac{a \times b}{F\lambda} \quad (6)$$

(Giri and Tesche, 2003)

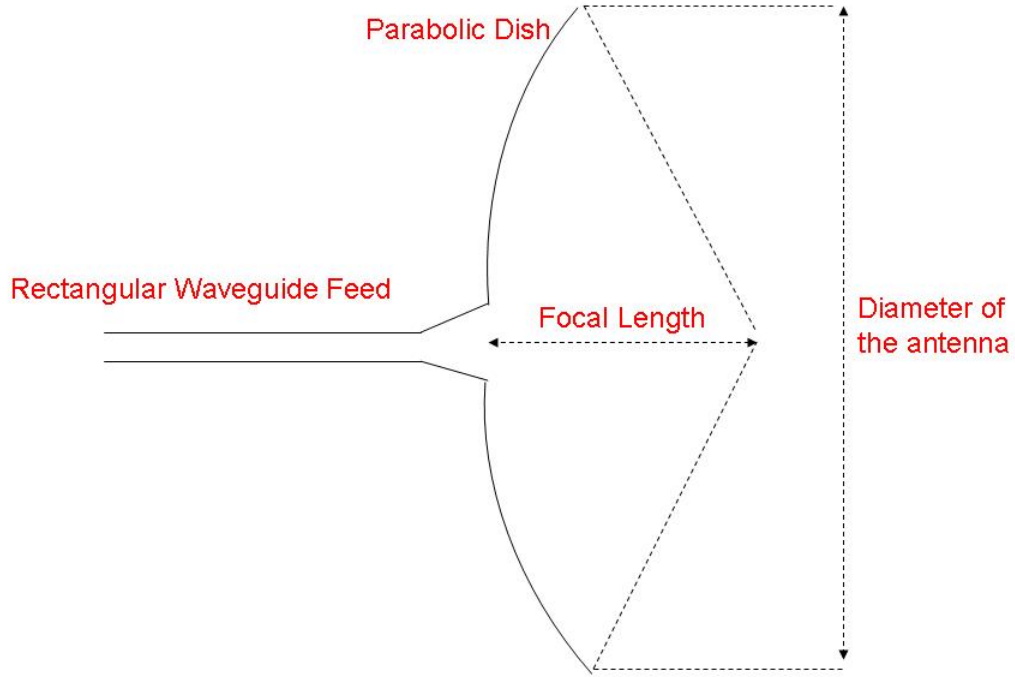


Figure 20. Aperture details of the proposed parabolic dish antenna

Once the electric field at the aperture of the antenna is found, the far field parameters may then be estimated by

$$E_{peak} (far field) = E_{peak} (at the aperture) \times \left(\frac{area of the reflector}{r\lambda} \right) V / m \quad (7)$$

$$p_{avg} (far field) = \left[\frac{E_{peak}^2 (at the aperture)}{2Z_0} \right] Watts / m^2 \quad (8)$$

$$u = p_{avg} \times \tau \quad Joules / m^2 \quad (9)$$

where

r : target distance (in meter) from the e-bomb

$E_{peak}(far\ field)$: E-field strength from the e-bomb at the
distance r

area of the reflector : $a \times b$ for the horn antenna

$\pi \frac{d^2}{4}$ for the parabolic antenna where d is the
diameter of the parabolic dish

$p_{avg}(far\ field)$: average power density

u : energy density (Taylor and Giri, 1994) (Giri and
Teschke, 2003) (Giri, 2004).

The field strength at one meter from the antenna is called the figure of merit (FOM). According to the far field parameters, the E-field and range product gives the FOM of the e-bomb. FOM provides a convenient comparative performance measure for HPM device outputs that is conveniently and easily scaled to the device peak field output at ranges beyond far-field.

As the microwave signal propagates through the troposphere, it is attenuated through energy absorption by atmospheric gases and by rain. Rain droplets also scatter as well as absorb microwave transmissions; however, the scattering of energy out of a beam is small when compared to the absorption loss.

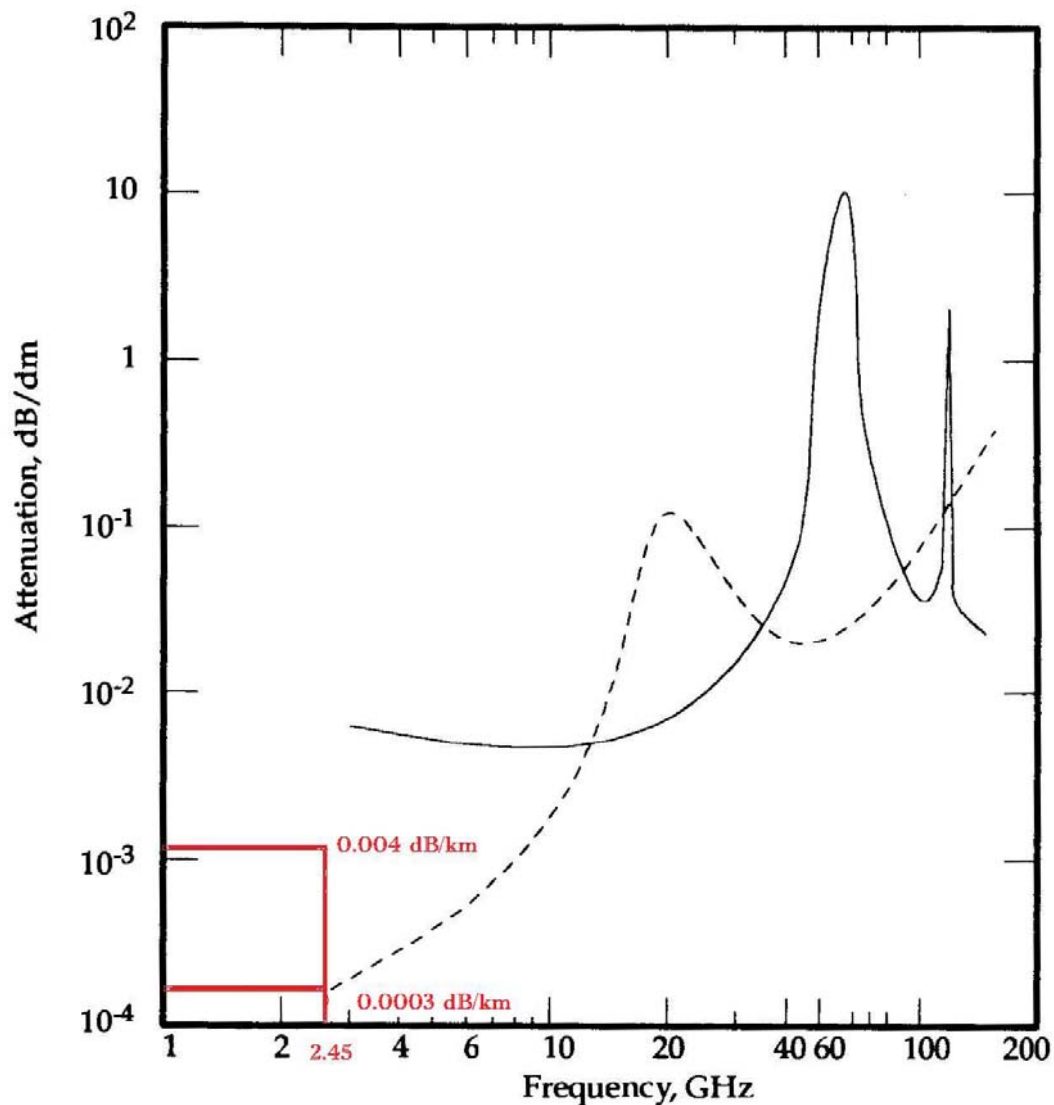


Figure 21. Atmospheric attenuation of microwave propagation at 0° C and 1 atm due to oxygen and water absorption (Taylor and Giri, 1994).

According to Figure 21, the attenuation due to the atmosphere is not significant below 1GHz. Consider the commonly used frequency at 2.45 GHz, where commercially available devices such as microwave ovens, cell phones etc. are operated. Among these devices, a microwave oven source can be used as a general HPM generator for an e-bomb. Any later HPM sources that will be defined as the source of e-bombs in this study will not be operated more than 2.45 GHz. Since the atmospheric attenuation increases by the frequency, the

maximum frequency in this study (2.45 GHz) will be used as the reference frequency for the upper limit of atmospheric attenuation. For the microwave oven operating frequency (2.45 GHz), the atmospheric attenuation is around 0.0003 dB/km. Since for the e-bomb simulation any loss in the HPM source, in the waveguide and at the reflector is neglected, 0.004 dB/km attenuation is chosen as the default atmospheric attenuation in order to fully compensate any ignored losses and provide a conservative output estimate.

Attenuation (loss) due to the rain is estimated by

$$L_R = xR^y \text{ dB/km} \quad (10)$$

where R is the rain rate in millimeters/hour. The constants x and y are dependent on operating frequency according to

$$x = x_1 f^{x_2} \quad f \text{ in GHz} \quad (11)$$

where

$$x_1 = 6.39 \times 10^{-5} \quad x_2 = 2.03 \quad f < 2.9 \text{ GHz} \quad (12)$$

$$x_1 = 4.21 \times 10^{-5} \quad x_2 = 2.42 \quad 2.9 \text{ GHz} \leq f \leq 54 \text{ GHz} \quad (13)$$

and

$$y = y_1 f^{y_2} \quad f \text{ in GHz} \quad (11)$$

where

$$y_1 = 0.851 \quad y_2 = 0.158 \quad f < 8.5 \text{ GHz} \quad (12)$$

$$y_1 = 1.41 \quad y_2 = -0.0779 \quad 8.5 \text{ GHz} \leq f \leq 25 \text{ GHz} \quad (13)$$

$$y_1 = 2.63 \quad y_2 = -0.272 \quad 25 \text{ GHz} \leq f \leq 180 \text{ GHz} \quad (14)$$

(Taylor and Giri, 1994)

Figure 22 shows the attenuation due to the rain for different rain rates at interested frequencies. The attenuation increases when the operating frequency increases. It also increases when the rain rate increases. For moderate rainfall, $R = 5 \text{ mm/h}$, the corresponding path loss is 0.00038 dB/km at 1.2 GHz, 0.0008 dB/km at 1.7 GHz, 0.0012 at 2 GHz, and 0.002 dB/km at 2.45 GHz.

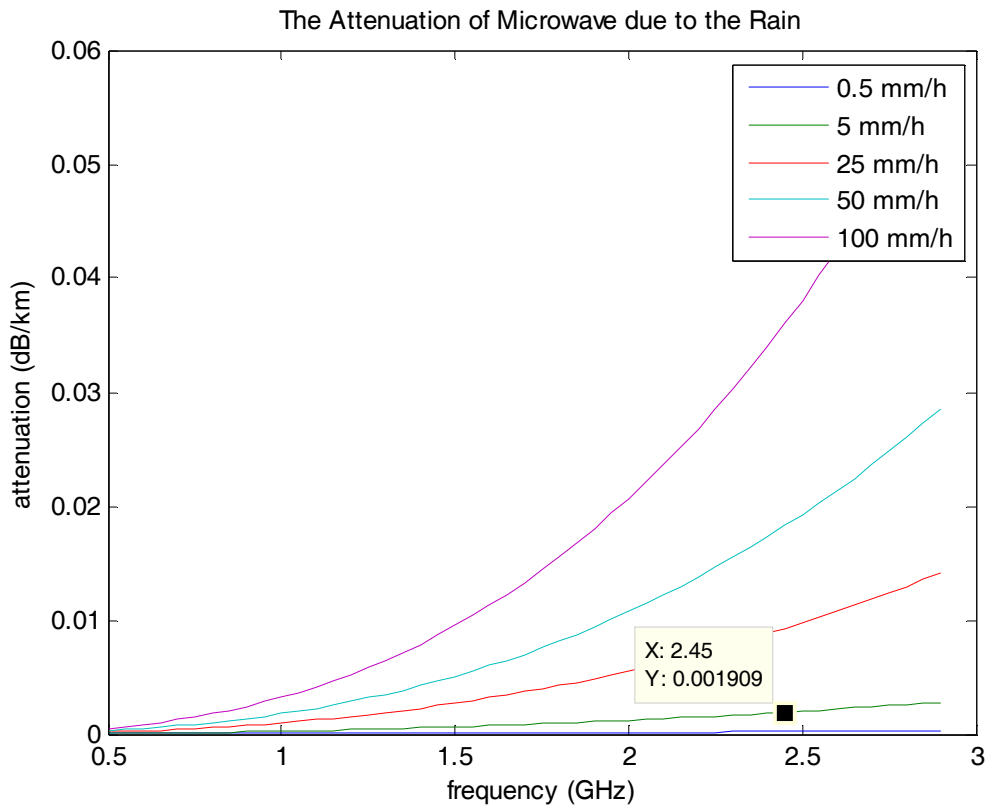


Figure 22. Attenuation of microwave due to the rain at different rain rates.

Up to this point, the basic theory for the hypothetical e-bomb is defined including the propagation features in the atmosphere. This theory as described will be used as the basis for MATLAB simulation calculation.

2. Classifications of the Source Elements

To show a wide range of different applications, source technologies and the range of effects on different targets, three types of e-bomb will be categorized and evaluated:

- Low-Tech (Small) E-Bomb
- Medium-Tech (Moderate) E-Bomb
- High-Tech (Powerful) E-Bomb

a. Low-Tech (Small) E-Bomb

A low-tech e-bomb is characterized by marginal performance, minimal technical capabilities, and is easily assembled and deployed (Giri and Tesche, 2003).

For this thesis, it will be assumed that low-tech (small) e-bombs will be used against relatively small and unshielded systems. Unshielded systems are considered to be fully exposed by e-bomb electromagnetic waves.

Low power levels are generally in the kW levels (Giri, 2004). For the simulation, a microwave oven specifications will be used to define the low-tech e-bomb. There are commercially available magnetron microwaves in the range of 800-2000 watts, which makes for an easily procured HPM generator.

Though militarily not applicable, the purpose of using a microwave oven source is to show that low-tech e-bomb designed from commercially available sources with average power level between 800-2000 watts are possible to produce field strength levels at about kV/m level at km distances with a reasonable antenna.

A commercially available continuous wave (CW) microwave oven has the operating frequency of 2.45 GHz. From Table.1, corresponding rectangular waveguide can be either WR340 or WR430. For this study, both waveguides will be used. According to the outputs of each e-bomb (WR340 and

WR430), the better output of the two will be chosen for the analysis of low-tech e-bomb. It will also set a rule to choose the appropriate waveguide in situations presenting more than one option.

For radiating the low-tech e-bomb output, a parabolic (dish) antenna with 1.54 m^2 aperture area ($d=1.4\text{m}$) with 0.371m focal length (F) will be used where d is the diameter of the dish antenna. Focal length and aperture area are chosen arbitrarily, but it is clear that such an antenna is available commercially. As mentioned before, the pulsewidth is chosen to be 100ns . Specifications for the “Low-Tech (Small) E-Bomb” are shown in Table. 2.

Operating frequency (f)	2.45 GHz
Average power (P_{avg})	800-2000 watts
WR340 waveguide dimensions ($a \times b$)	0.086x0.043 m
WR430 waveguide dimensions ($a \times b$)	0.10922x0.05461 m
Aperture area of the reflector (A)	1.54 m^2 ($d=1.4 \text{ m}$)
Focal length of the reflector (F)	0.371 m
Pulsewidth (τ)	100 ns

Table 2. Specifications of Low-Tech (Small) E-Bomb

b. Medium-Tech (Moderate) E-Bomb

The medium-tech e-bomb, as defined in this thesis, requires the skills of a qualified electrical engineer and relatively more sophisticated components such as commercial radar systems that can be modified to become a weapon system like e-bomb (Giri and Tesche, 2003).

For the simulation, it will be assumed that medium-tech (moderate) e-bombs will be used against moderately shielded systems. A 30 dB shielding

effectiveness is assumed for moderately shielded systems. Civil aviation aircraft provide a good example for moderately shielded systems that might have roughly 30 dB shielding.

It is known that sufficiently intense electromagnetic signals in the frequency range of 200 MHz to 5 GHz can cause electronic damage in many systems. For the simulation of medium-tech e-bomb, 1.2 GHz and 1.7 GHz are chosen as the operating frequencies due to their common applicability to standard radar and communications technologies that are similar in form. Moderate power levels can be in the range of 1 to 20 MW (Giri, 2004). For the average power, a range between 1-20 MW will be analyzed to decide the most effective power source and operating frequency. There are also commercially available radar systems that operate around 1.2 GHz and 1.7 GHz frequency level and radiate an average power up to 20 MW.

For the medium-tech e-bomb, corresponding rectangular waveguides are chosen to be WR770 for 1.2 GHz frequency and WR650 for 1.7 GHz frequency from Table.1. After comparing the outputs of each frequency option of the moderate e-bomb, a conservative estimate will be identified that covers the largest output from the two as the medium-tech (moderate) e-bomb for the analysis the potentially lethal effect on different systems.

Based on the initial work by Giri (Taylor and Giri, 1994), a parabolic (dish) antenna with 4.9 m^2 aperture area ($d=2.5\text{m}$) with 0.5m focal length (F) will be used for reflector of the medium-tech e-bomb. Focal length and aperture area are chosen arbitrarily. The pulsewidth is to be 100ns (as was done for low-tech e-bomb). Specifications for the “Medium-Tech (Moderate) E-Bomb” are shown in Table.3.

Operating frequency (f)	1.2 GHz and 1.7 GHz
Average power (P_{avg})	1-20 MW
WR650 waveguide dimensions ($a \times b$)	0.1651x0.08255 m
WR770 waveguide dimensions ($a \times b$)	0.19558x0.09779 m
Aperture area of the reflector (A)	4.9 m ² (d=2.2 m)
Focal length of the reflector (F)	0.5 m
Pulsewidth (τ)	100 ns

Table 3. Specifications of Medium-Tech (Moderate) E-Bomb

c. High-Tech (Powerful) E-Bomb

More sophisticated high-tech and high-power electromagnetic systems would certainly require specialized and sophisticated technologies and perhaps even specifically tuned output to cause severe damage to a specific target (Giri, 2004).

For the e-bomb simulation, it will be assumed that high-tech (powerful) e-bombs will be used against fully shielded systems. A 40-50 dB shielding effectiveness is assumed for fully shielded systems. Military systems are a good example of fully shielded systems and are procured with shielding requirements in order to perform designed missions.

Following the initial work by Giri (Taylor and Giri, 1994), The operating frequency of high-tech (powerful) e-bomb is chosen to be 2 GHz. High power levels can be in the range of 100's of MW to GW's (Giri and Tesche, 2003). For the average power, a 20 GW source will be used to assess the effects of powerful e-bomb on target systems. A 20 GW vircator source has been reported by Benford in 1987 (Benford, 2004). Obviously, the technology has

been improved for the past 20 years and more power is achievable with a reasonable, compact size. Once the lethality generated by a 20 GW source is assessed, one can easily think about the effects of possible lethality level generated by the current technology.

For the high-tech e-bomb, corresponding rectangular waveguide is chosen to be WR510 from Table.1.

A horn antenna with 12.5 m^2 aperture area (5x2.5m) will be used for the high-tech e-bomb. The horn dimensions are chosen arbitrarily. The pulsewidth is to be 100ns. Specifications for the “High-Tech (Powerful) E-Bomb” are shown in Table. 4.

Operating frequency (f)	2 GHz
Average power (P_{avg})	20 GW
WR510 waveguide dimensions ($a \times b$)	0.12954x0.06477 m
Aperture area of the horn (A)	12.5 m^2 (5x2.5 m)
Pulsewidth (τ)	100 ns

Table 4. Specifications of High-Tech (Powerful) E-Bomb

B. COUPLING ESTIMATES

All electronic equipment is susceptible to malfunctions and permanent damage under electromagnetic illumination of sufficient intensity. The intensity level for system vulnerability is dependent upon the coupling from the external fields to the electrical circuits and their corresponding sensitivity characteristics.

A temporary malfunction (or upset) can occur when an illuminating electromagnetic field induces current and voltages in the operating system electronic circuits at levels that are comparable to the normal operating signals. Permanent damage can occur when these induced stresses are at levels that

produce joule heating to the extent that thermal damage occurs. (usually between 600 and 800 degrees Kelvin) (Benford, Swegle, and Schamiloglu, 2007).

No matter what kind of e-bomb is used or which power/frequency/mode is applied, two principal coupling modes are recognized in open literature in assessing how much power is coupled into target systems:

- Front Door Coupling
- Back Door Coupling

Both coupling mechanisms are explained here, although, only the back door coupling will be used in the simulation in order to assess the lethality of three classes of hypothetical e-bombs. Considering that front door coupling inherently has more energy delivered into target systems than the energy delivered through back door coupling, it can be assumed that, in reality, more susceptibility can be achieved than the susceptibility shown in this study.

All the coupling estimates will assume that the target system is in the main lobe of the e-bomb antenna. Clearly, if the target is in the sidelobes or at random angles, the coupling efficiency will decrease, and less power will be delivered to the target.

1. Front Door Coupling

Front Door Coupling is typically observed when the power radiated from the e-bomb is directly coupled into the electronic systems, which involves an antenna such as radars, EW or communications equipments. The antenna subsystem is designed to couple power in and out of the equipment, and thus provides an efficient path for the power flow from the electromagnetic weapon to enter the equipment and cause damage (Kopp, 1996).

For front door coupling to gain entry through an antenna, it can be appropriate to operate the e-bomb at the in-band frequency of target system if it

is known (Benford, Swegle, and Schamiloglu, 2007). For this reason, most front door coupling is efficient for only a narrow band of frequency, and is inefficient outside the band.

2. Back Door Coupling

Back Door Coupling occurs when the electromagnetic field from the e-bomb produces large transient currents (termed spikes, when produced by a transient source) or electrical standing waves (when produced by a HPM weapon) thru cracks, small apertures and on fixed electrical wiring and cables interconnecting equipment, or providing connections to power mains or the telephone network. Equipment connected to exposed cables or wiring will experience either high voltage transient spikes or standing waves, which can damage power supplies and communications interfaces if not shielded or inherently robust. Moreover, should the transient penetrate into the equipment, other devices inside can be damaged through mutual coupling. Any cable can comprise multiple linear segments, which are typically at close to right angles; therefore, whatever the relative orientation of the e-bomb, one or more segments can provide very good coupling efficiency. Network cables use fast, low-loss dielectrics and are thus very efficient at propagating such transients with minimal loss (Kopp, 1996). Back door coupling can generally be described as wideband, but may have narrow-band characteristics because of resonance effects (coupling to cables for example).

Theory for the back door coupling is more complex than that for the front door coupling. Since the cross section of coupling is difficult to determine for the target system, the susceptibility results can be different from the expected (Benford, Swegle, and Schamiloglu, 2007).

For the validation of the hypothetical e-bomb model and the assessment of each e-bomb's lethality, a basic theory relating field strength to coupled current will be used in the simulation.

The point form of Ohm's Law indicates that the conduction current density generated on a wire or a coaxial cable depends on the conductivity of that material and the electric field strength that the wire/coaxial cable is subjected to. Current density in Ampere/square meter is given by

$$J = \sigma E \quad \text{A/m}^2 \quad (15)$$

where

σ : Conductivity of material (target system design)

E : E-field strength that the wire/coaxial cable is subjected to (Ulaby, 2006).

The conductivity of the materials used in the simulation is shown in Table.5.

Material	Conductivity, σ Siemens/meter (S/m)
Silver	6.2×10^7
Copper	5.8×10^7
Gold	4.1×10^7
Aluminum	3.5×10^7
Iron	10^7

Table 5. Conductivity of materials used in the simulation (Ulaby, 2006)

Once the current density is determined, for an arbitrary surface S, the total current flowing through that surface is given by

$$I = \int_S J \cdot ds \quad \text{Ampere (A)} \quad (16)$$

For circular wire, equation (16) becomes

$$I = J \left(\frac{\pi d_w^2}{4} \right) \quad (17)$$

where

- J : Current density
- d_w : Diameter of the wire (Ulaby, 2006).

For coaxial cables, equation (16), the surface integration, becomes

$$I = J(2\pi r_c l) \quad (18)$$

where

- J : Current density
- r_c : Radial distance of coaxial cable from the axis
of the center conductor
- l : Length of coaxial cable (Ulaby, 2006).

Once the total current flowing through the wire/cable is determined, the coupled power can be expressed by

$$P_c = I^2 R_m \quad (19)$$

where

- P_c : coupled power
- R_m : matched load of the target system.

Using the field-current relationships, the coupled power into the target system is compared with known electromagnetic susceptibility limits of electronic circuits and components in order to determine the potential susceptibility of each e-bomb against different targets.

C. EFFECTS ON TARGETS

E-bomb interactions with system electronics can be categorized in four levels of destructive effect (upset, lock-up, latch-up, and burnout) and are dependent upon:

- Distance to the target
- Vulnerability of the target
- Operating frequency
- Coupled power level and power density on the target
- Bandwidth
- Burst rate and pulse duration
- Dwell time on the target
- Coupling mode or entry points

These four potential effects of e-bombs on targets can be categorized into a hierarchy of lethality (described in the following paragraphs), each of which require increasing microwave emission on the target.

1. Soft-Kill

A soft kill is produced when the effects of the weapon cause the operation of the target equipment or system to be temporarily disrupted. A good example is a computer system, which is caused to reset or transition into an unrecoverable or hung state. The result is a temporary loss of function, which can seriously compromise the operation of any system that is critically dependent upon the computer system in question (Kopp, 1996).

Soft kill can occur in two forms:

a. Upset

Upset is a temporary alteration of the electrical state of one or more nodes, in which the nodes no longer function normally. Upset means particular interaction as observed between a weapon and the operating state of the target system at the time, as the state changes, upsets could subside. Given operating state, the upset continues until the impressed radiation is terminated. Once the

signal is removed, the affected system can be easily restored to its previous condition. Interference caused by jamming equipment or lightning are examples of this type of deny effect (Deveci, 2007).

b. Lock-up

Lock-up is similar to upset in that the electrical states of affected nodes are temporarily altered, but the functionality of these nodes remains altered after the radiation is removed. Lock-up produces a temporary alteration similar to upset, but electrical reset or shut off and restart is necessary to regain functionality after the radiation is removed. Degrading is an example that requires the intervention by an external operator or special safeguard procedures to reload the target system (Deveci, 2007).

2. Hard-Kill

A hard kill is produced when the effects of the weapon cause permanent electrical damage to the target equipment or system, necessitating either the repair or the replacement of the equipment or system in question. An example is a computer system that experiences damage to its power supply, peripheral interfaces and memory. The equipment may or may not be repairable, subject to the severity of the damage, and this can, in turn, render inoperable — for extended periods of time — any system that is critically dependent upon this computer system (Kopp, 1996).

Hard kill can be seen in two forms:

a. Latch-up

Latch-up is an extreme form of lockup in which parasitic elements are excited and conduct current in relatively large amounts until either the node is permanently self-destroyed or the electrical power is switched off to the node. This effect can run down batteries supplying power to the affected nodes or can

pull down power supply voltages. No responding semiconductor devices to an input or transistors failing on a circuit board due to overloads from radiation are two latch-up examples (Deveci, 2007).

b. Damage/Burnout

Damage/burnout is electrical destruction of a node by some mechanism like latch-up, metallization burnout, or junction burnout. Because electrical overstress can cause charge buildups in passivation layers and dielectric layers that decay with the time, damage is often distinguished as to its degree of performance. One will often find the term “permanent damage” or “electrical burnout” used to describe the more catastrophic kinds of damage. Damage/burnout occurs when the high-power microwave energy causes melting in capacitors, resistors or conductors. Burnout mostly occurs in the junction region where multiple wires or the base collector or emitter of a transistor come together, and often involves electrical arcing. Consequently, the heating is localized to the junction region. A lightning strike’s effect on electronic devices is a burnout example (Deveci, 2007).

D. MODEL

It is far too complicated to ideally and faithfully represent the effects of proposed e-bombs through back-of-envelope calculation methods since it involves a wide range of interacting and interdependent parameters and equations. However, reliable and dependable predictions for coupling to a wide variety of electric circuitry environments and components are still needed and valuable when used to assess the potential effects of e-bombs. For this reason, a MATLAB simulation is used to simulate each type of described e-bomb. The flow diagram of this simulation is shown on Figure 23. The output designated by the numbers is the output plots of the simulation and defined in the next paragraph.

The MATLAB code for the simulation is shown in Appendix-B. The model’s output is:

- The maximum E-field that can propagate in the air without breakdown
- Minimum dimensions of the horn antenna in order to avoid the breakdown in the air
- “E-field strength vs. the distance” plot of e-bomb (without loss) (1)
- “E-field strength vs. the distance” plot of e-bomb with atmospheric loss (2)

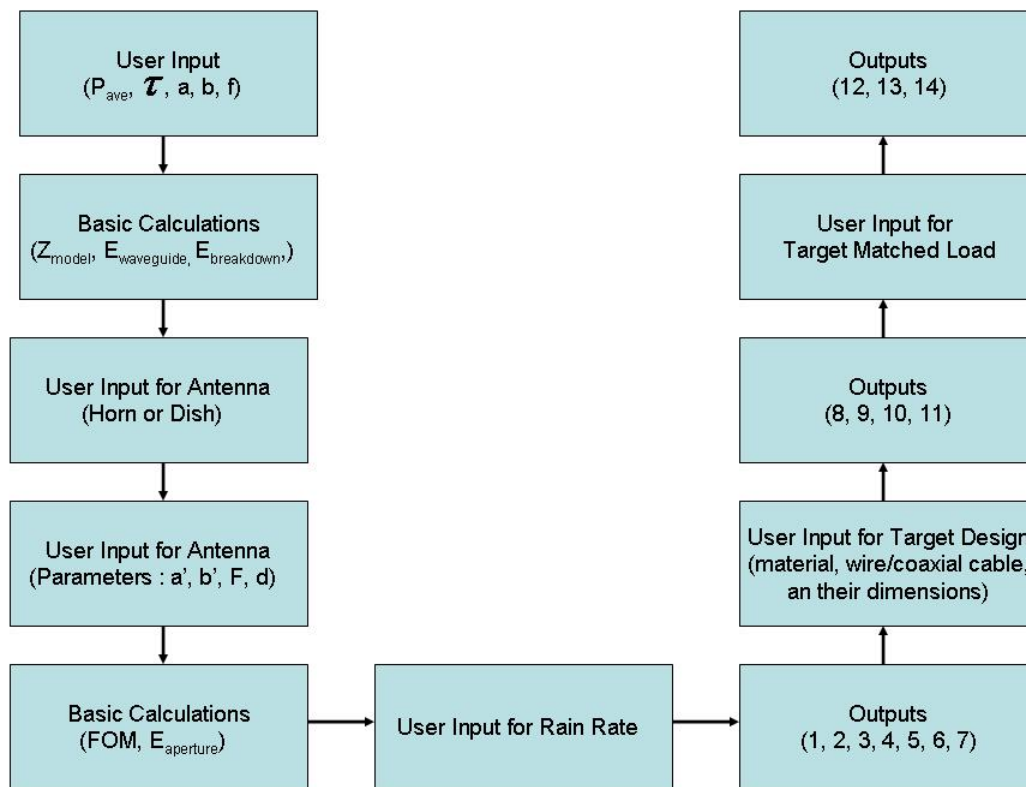


Figure 23. Flow Diagram of MATLAB Simulation

- “E-field strength vs. the distance” plot of e-bomb with atmospheric loss + loss due to rain (3)
- “Average power density vs. the distance” plot of e-bomb with atmospheric loss (4)

- “Average power density vs. the distance” plot of e-bomb with atmospheric loss + loss due to rain (5)
- “Energy density vs. the distance” plot of e-bomb with atmospheric loss (6)
- “Energy density vs. the distance” plot of e-bomb with atmospheric loss + loss due to rain (7)
- “Flowing current vs. the distance” plot of e-bomb with atmospheric loss (for chosen material) (8)
- “Flowing current vs. the distance” plot of e-bomb with atmospheric loss + loss due to rain (for chosen material) (9)
- “Flowing current vs. the distance for shielded systems” plot of e-bomb with atmospheric loss (for chosen material) (10)
- “Flowing current vs. the distance for shielded systems” plot of e-bomb with atmospheric loss + loss due to rain (for chosen material) (11)
- “Delivered power vs. the distance for unshielded” plot of e-bomb for atmospheric loss and rain loss (for chosen material and chosen matched load) (12)
- “Delivered power vs. the distance for shielded systems” plot of e-bomb with atmospheric loss (for chosen material and chosen matched load) (13)
- “Delivered power vs. the distance for shielded systems” plot of e-bomb with atmospheric loss + loss due to rain (for chosen material and chosen matched load) (14)

According to the results obtained from the simulation, a susceptibility assessment is performed and critically analyzed. Finally, an assessment of military utility is conducted.

E. VALIDATION OF THE MODEL

Consider a scenario that includes a medium-tech (moderate) e-bomb used against a commercial airplane. The e-bomb in this scenario will be radiating microwave energy 500 feet away from the airplane. The inherent question is, “Can medium-tech e-bombs generate a field strength or deliver a force into the airplane electronic systems, such as radars, communication devices, electronic modules etc., that cause damage to important electronic devices?”

The answer to this question leads to the need to validate the proposed simulation in this thesis. A validated model adds credibility to the results obtained in terms of expected “real world” coupling effects. Such a validation scenario is shown in Figure 24.

For this scenario, a medium-tech (moderate) e-bomb is used in the system interaction estimations. As mentioned before, the interested target for moderate e-bomb is civil aviation. It is assumed that the electrical systems on the airplane involve coupling to a representative cable that is 100 ohms impedance matched to a load circuit. The specifications for the moderate e-bomb is shown in Table 6. All specifications are chosen to be arbitrary, but, at the same time, providing specifications that meet the criteria defined in moderate e-bomb classifications.

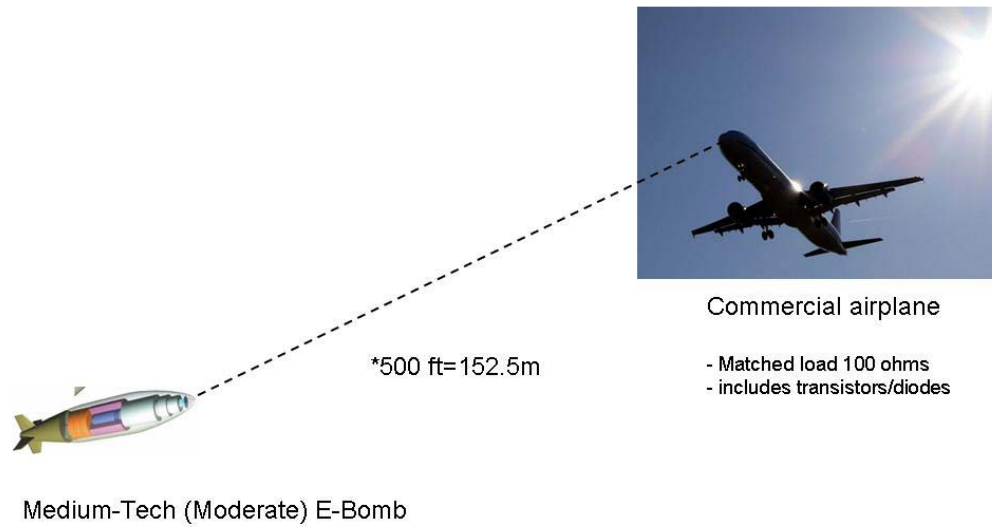


Figure 24. Scenario for validation of e-bomb simulation

Operating frequency (f)	1.2 GHz
Average power (P_{avg})	700 kW
WR770 waveguide dimensions ($a \times b$)	0.19558x0.09779 m
Aperture area of the reflector (A)	3.14 m ² (d=2 m)
Focal length of the reflector (F)	0.5 m
Pulsewidth (τ)	100 ns

Table 6. Moderate E-Bomb specifications for validating scenario

As a first step and upon completing a simulation run, the results of the simulation are compared to the (High Intensity Radiated Field) HIRF Environment Standards for commercial aircrafts.

The HIRF environment standards guide is a document that provides technical guidance to demonstrate compliance with best-practice aircraft high intensity radiated field certification regulations. The HIRF regulations are applicable to any civilian aircraft. The more specific area of applicability to each aircraft is the continued availability of functions related to safe takeoff, flight, and landing during and after exposure to HIRF. It must be demonstrated and certified that aircraft systems that perform functions related to safe takeoff, flight, and landing must not be lost when the aircraft is exposed to the Severe or Certification HIRF Environment (HIRF Standards, 2003).

The environments were defined from considering all deployed emitters operating at peak output located in the continental United States, Hawaii, Alaska and Puerto Rico, plus the five participating European countries: United Kingdom, Germany, Sweden, France, and the Netherlands (HIRF Standards, 2003).

The external environment is found to exist due to the radiation of Radio Frequency (RF) electromagnetic energy into free space. This energy is radiated from radio, television, radar emitters, and from other sources. Figure 25 depicts many of these common electromagnetic sources that couple to and cause interference with electrical wiring of aircraft. Two of these sources of great concern to the aircraft designers and manufacturers are the high-energy external RF emissions from radars and radio transmitters and the effects of direct and indirect lightning. Contributing to the electromagnetic environment are more than 500,000 emitters in the U.S. and Western Europe. The HIRF environments are a composite of transmitters that are airborne, land-based, offshore platforms, and ship-based. These transmitters are becoming more sophisticated, more efficient, more powerful, and more numerous. The emitters cover the entire Radio Frequency (RF) spectrum and their radiated fields vary greatly in energy levels and signal characteristics.

The Severe HIRF Environment is based on the “worst case” estimate of electromagnetic field strengths that a civil aircraft might encounter.

The International Civil Aviation Organization (ICAO) flight standards allow flight to within 500 feet of the ground under visual flight rules (VFR) for fixed wing aircraft. Although this is uncommon for many aircrafts, it is permissible. At such an altitude, aircraft have the potential to come extremely close to terrestrial-based emitters that produce RF field levels at the aircraft in excess of 7,000 volts/meter. This resulted in the committee establishing two Severe HIRF environments, one for fixed wing aircraft and one for rotorcraft. The material in HIRF standards deals only with flights above 500 feet except during landing and takeoff at civil airports (HIRF Standards, 2003).

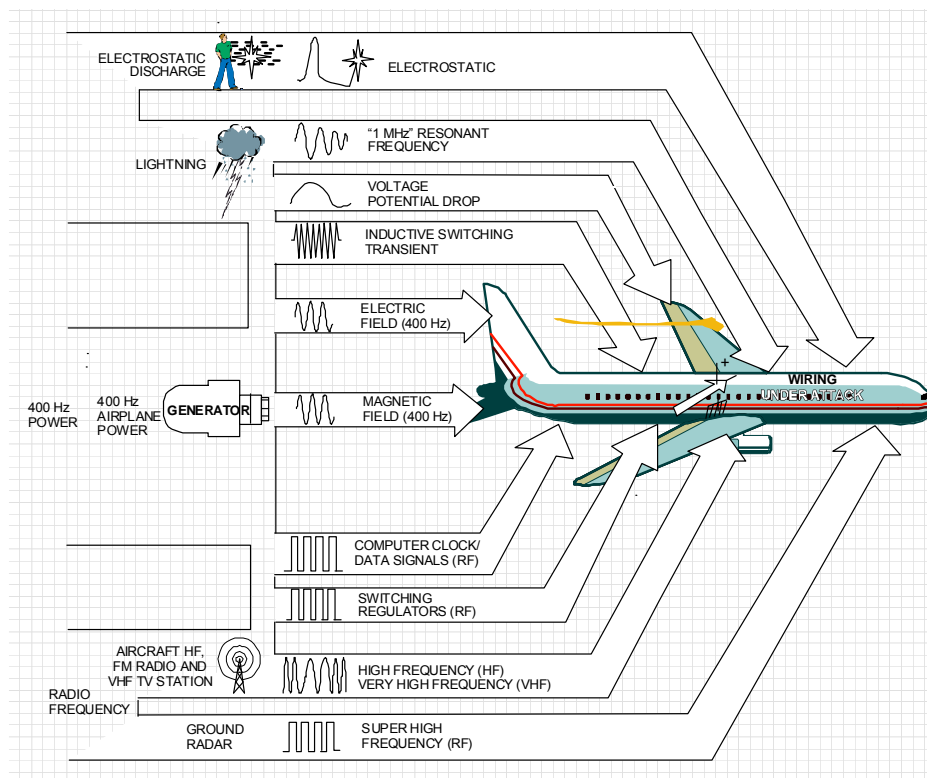


Figure 25. HIRF Environment for an aircraft

The Fixed Wing Severe HIRF Environment is defined as “the worst case estimate of the electromagnetic field strength levels in which the airspace in which fixed wing flight operations are permitted” (HIRF Standards, 2003).

For the simulation in this study, Fixed Wing Severe HIRF Environment is used to compare the output of the study. These composite levels are shown as a function of frequency in Table 7.

FREQUENCY	FIELD STRENGTH (V/m)	
	PEAK	AVERAGE
10 kHz – 100 kHz	50	50
100 kHz – 500 kHz	60	60
500 kHz – 2 MHz	70	70
2 MHz – 30 MHz	200	200
30 MHz – 70 MHz	30	30
70 MHz – 100 MHz	30	30
100 MHz – 200 MHz	90	30
200 MHz – 400 MHz	70	70
400 MHz – 700 MHz	730	80
700 MHz – 1 GHz	1400	240
1 GHz – 2 GHz	3300	160
2 GHz – 4 GHz	4500	490
4 GHz – 6 GHz	7200	300
6 GHz – 8 GHz	1100	170
8 GHz – 12 GHz	2600	330
12 GHz – 18 GHz	2000	330
18 GHz – 40 GHz	1000	420

Table 7. Fixed Wing Severe HIRF Environment (HIRF Standards, 2003)

The second step to validate the model is to show whether the generated E-field is sufficient to couple enough power into the target system. For this reason, estimated coupled power into the target is compared to published damage threshold levels for devices such as representative transistors, SCRs, diodes, and integrated circuits. A valuable damage threshold level report was published by Defense Nuclear Agency (DNA) in 1977. DNA defined the damage threshold levels in kilowatts of the power. A damage threshold power range derived from experimental evidence and representative devices is demonstrated by the horizontal bars in Figure 26. According to the data shown in the figure, a damage threshold power may be as low as 1 watt for microwave diodes or as high as 40 kW for high power transistors.

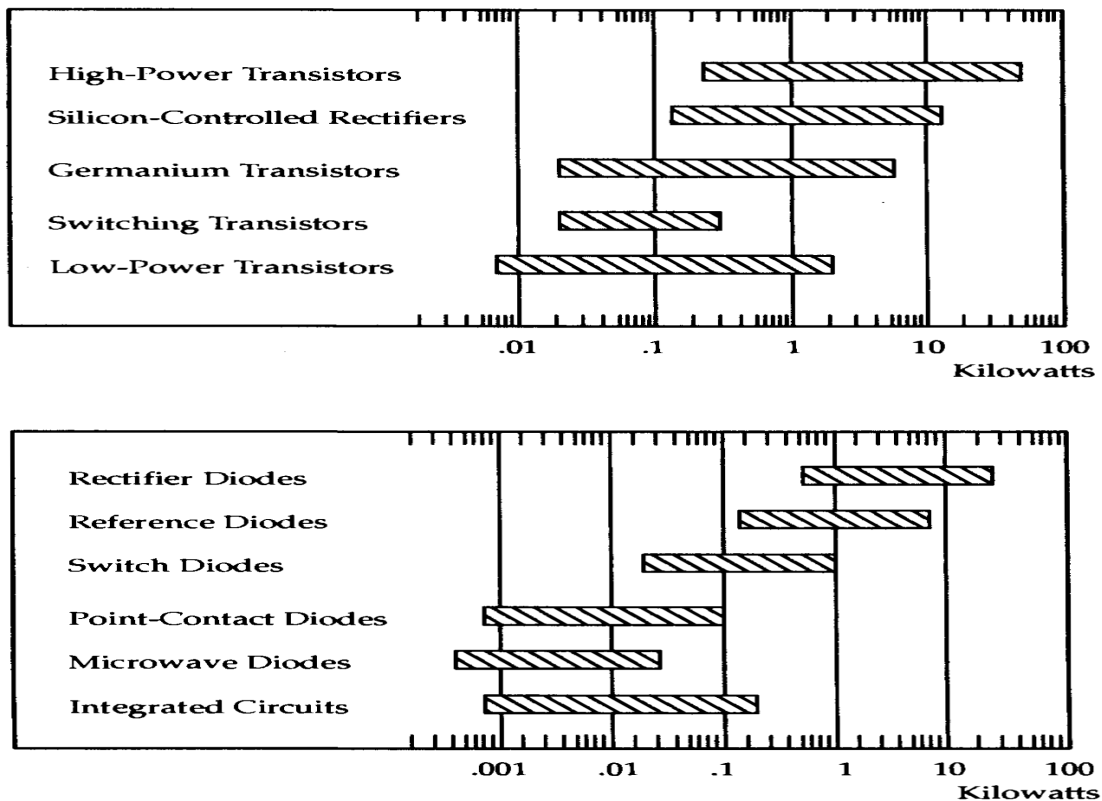


Figure 26. Damage threshold power range of representative transistors, SCRs, diodes, and integrated circuits (Mendel, 1997)

The airplane in the chosen scenario is assumed to have a 30 dB shielding (moderate). The 30 dB shielding also corresponds to the level of shielding that is necessary for the avionics in civil aircraft and helicopters in order to withstand the radar frequency HIRF environment (Bäckström, and Lövstrand, 2004).

For the medium source representation of an e-bomb specified in Table 6, a field strength at 267.9 kV/m is created in the waveguide. Since it is less than the breakdown field strength, 3.1 MV/m, no vacuum is required for the waveguide. The generated E-field at the aperture of the antenna from this waveguide field is then about 41 kV/m, which is also less than the breakdown level. The corresponding FOM is 514 kV/m. (recall that FOM is the far-field output of the device as it would be measured one-meter from the source antenna and in the direction of maximum field output).

Using the FOM, estimates at far-field electromagnetic environments produced by the source can be easily generated as a function of range (Field strength = FOM/range). The E-field strength of moderate e-bomb with atmospheric losses vs. the range is shown in Figure 27. According to this figure, the hypothetical moderate e-bomb produces an E-field strength of 3.36 kV/m at 153 meters (500 feet is converted to 152.5 meters and approximated to 153 meters). Notice that this environment almost identically matches the HIRF threshold at 1 GHz for reliable equipment operations. The 3 kV/m result is therefore tagged as important and significant.

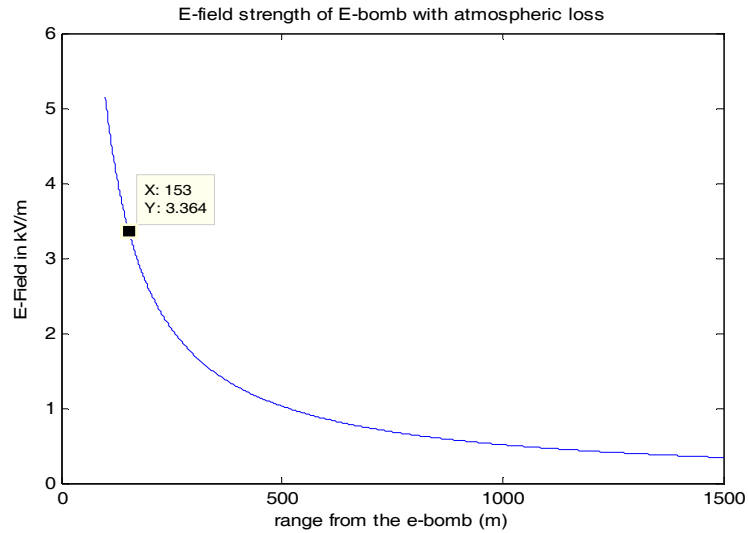


Figure 27. E-field strength of moderate e-bomb

If it is assumed that the civil airplane considered in the validation model has electrical equipment configuration that involve a 2 mm-diameter-copper wire (common), the coupled electric field delivers 613 A current into a matched, fully exposed, unshielded electronic system (see Figure 28).

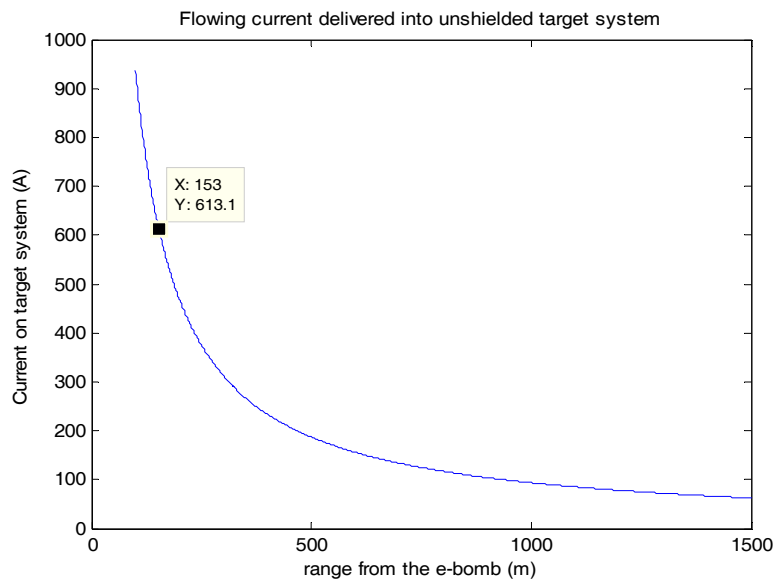


Figure 28. Current vs. the range plot of moderate e-bomb for unshielded systems

When the 30 dB shielding is applied to the simulation, corresponding current coupled into the system decreases to 19 A (see Figure 29).

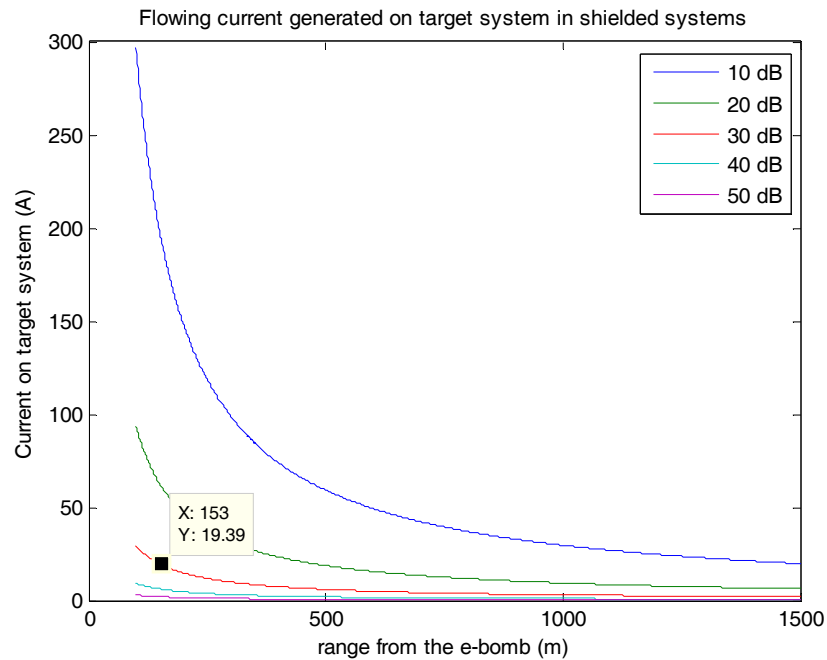


Figure 29. Current vs. the range plot of moderate e-bomb for shielded systems

Corresponding power coupled into the 30 dB-shielded target system is 37.6 kW for a 100 ohms-matched load circuit (see Figure 30)

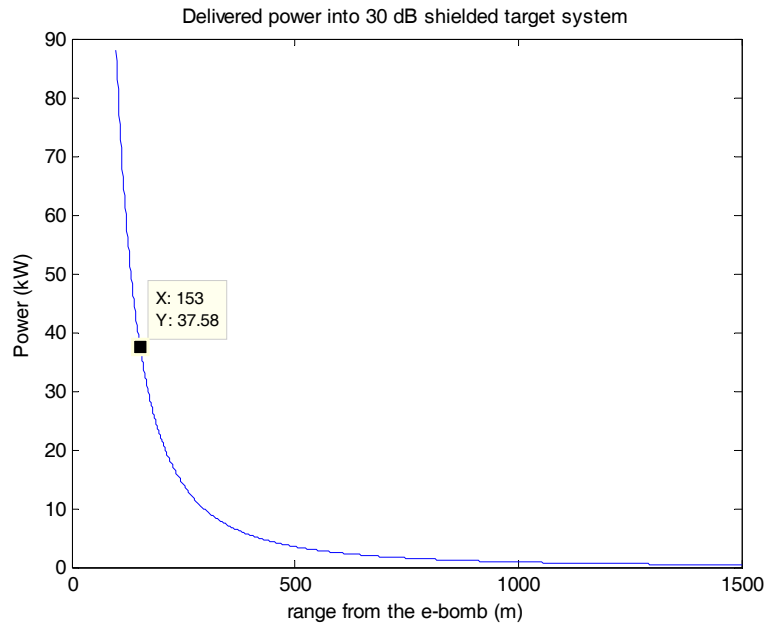


Figure 30. Delivered power into 30 dB shielded systems vs. the distance

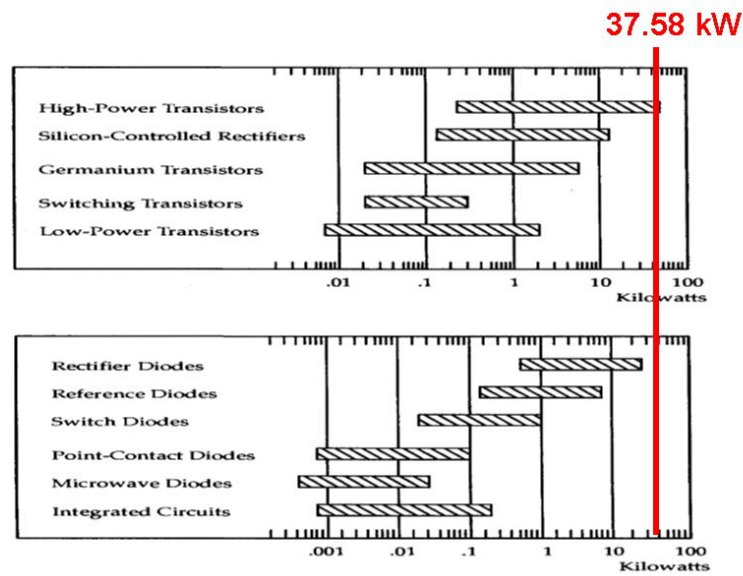


Figure 31. Delivered power into the 30 dB-shielded system

The power produced by the moderate e-bomb in 30 dB-shielded system falls on the upper side of the range for damage threshold levels of representative devices (see Figure 31). That means, the medium technology e-bomb in the scenario produces outputs on electronic equipments of a commercial airplane, which is 500 feet away from the e-bomb, that most likely exceed all known electromagnetic device damage susceptibility limits. The results show that the field strength produced by hypothetical moderate e-bomb is also consistent with the field data given by HIRF standards. (3.364 kV/m vs. 3.3 kV/m).

As a result, the scenario explained in this section validates the model developed to represent the hypothetical e-bomb. Model results are consistent with the HIRF environment thresholds and have exceeded all device damage limits. It is therefore a realistic expected exposure level and, because of the delivered power expected, it produces an important result. The validated model is used to assess the potential lethality effect of each type of e-bomb. HIRF standards in field strength have been tied to damage thresholds, so they are used as the reference to assess the potential lethality of e-bomb on commercial airplanes. Potential lethality is described because actual coupling levels in real (not modeled) systems will depend on many additional factors. This fact does not guarantee lethality, but does provide a condition of potential lethality based on our understanding of the system, the model used, and the database of damage criteria available.

F. POTENTIAL LETHALITY OF HYPOTHETICAL E-BOMB

The potential lethality of each type of e-bomb of interest depends on the target attacked. Targets are classified as:

- Unshielded Systems
- Moderately Shielded Systems
- Fully Shielded Systems

Unshielded systems are fully exposed by electric fields produced by radiating sources and will be considered in the interest of the low-tech (small) e-bomb. Moderately shielded systems are the systems that have 30 dB shielding. Civil aviation is in the interest of the medium-tech (moderate) e-bomb. In addition, civil aviation can be considered as moderately shielded systems according to the data, which is consistent with HIRF standards. Fully shielded systems are the systems that have 40-50 dB shielding effectiveness (SE). Military systems can be considered in this group and is in the interest of the high-tech (powerful) e-bomb.

The potential lethality ranges is estimated by using the known/published susceptibility levels from DNA reports as described earlier.

1. Low-Tech (Small) E-Bomb

The specifications for a low-tech e-bomb, as used in the simulation, are defined in Table 1. The low-tech simulation is run for each power level of the e-bomb. In the first step, it is assumed that the e-bomb is designed by using WR340 ($a=0.086$ m, $b=0.043$ m) waveguide. The output of the e-bomb is shown in Table 8.

P_{avg} (Watts)	E_{max} (waveguide) (kV/m)	E_{peak} (at the aperture) (kV/m)	FOM (kV)
800	21.55	1.75	22.06
900	22.86	1.86	23.04
1000	24.10	1.96	24.67
1100	25.27	2.06	25.87
1200	26.40	2.15	27.02
1300	27.47	2.24	28.12
1400	28.51	2.32	29.18
1500	29.51	2.40	30.21
1600	30.48	2.48	31.20
1700	31.41	2.56	32.16
1800	32.32	2.63	33.09
1900	33.21	2.70	34.00
2000	34.07	2.77	34.88

Table 8. Simulation output for field strengths of low-tech e-bomb with WR340 waveguide

If the e-bomb is designed by using WR430 ($a=0.10922$ m, $b=0.05461$ m) waveguide, the strength of the E-field produced by the low-tech e-bomb slightly increases. It also decreases the field strength in the waveguide. This must be noted in order to use as a rule of thumb for high-level powers. Output of the simulation is shown in Table 9.

P_{avg} (Watts)	E_{max} (waveguide) (kV/m)	E_{peak} (at the horn) (kV/m)	FOM (kV)
800	15.6	2.05	25.8
900	16.5	2.17	27.3
1000	17.4	2.29	28.8
1100	18.3	2.40	30.2
1200	19.1	2.51	31.6
1300	19.9	2.61	32.9
1400	20.6	2.71	34.1
1500	21.4	2.81	35.3
1600	22.1	2.90	36.5
1700	22.7	2.99	37.6
1800	23.4	3.07	38.7
1900	24.1	3.16	39.77
2000	24.7	3.24	40.8

Table 9. Simulation output for field strengths of low-tech e-bomb with WR430 waveguide

Given that the e-bomb includes WR430 waveguide and has two power levels, 1500 watts and 2000 watts, the produced field strength at a range 1 km from the e-bomb is 35.3 V/m for 1500 watts and 40.8 V/m for 2000 watts (see Table 9). These estimates do not include the atmospheric losses.

P_{avg} (watts)	E r = 1m	E r = 500 m	E r = 1 km
1500	35.3 kV/m	70.6 V/m	35.3 V/m
2000	40.8 kV/m	81.6 V/m	40.8 V/m

Table 10. Evaluation Field strengths of low-tech e-bomb at different ranges

Among the different power levels, a 2000-watts source is chosen with WR430 waveguide in order to estimate the potential lethality range for different types of targets.

Some of the simulation outputs for different parameters of the e-bomb are shown on Figure 32 (All simulation output for the low-tech e-bomb is shown in Appendix-C). The results show that for the ranges less than 1500 meters, the atmospheric loss due to the moderate rain is insignificant. Assuming a lossless propagation environment, the E-field strength at 1 km from the e-bomb is 40.8 V/m where E-field strength with atmospheric loss is 40.78 V/m and E-field strength with atmospheric loss and rain loss is 40.77 V/m at the same range.

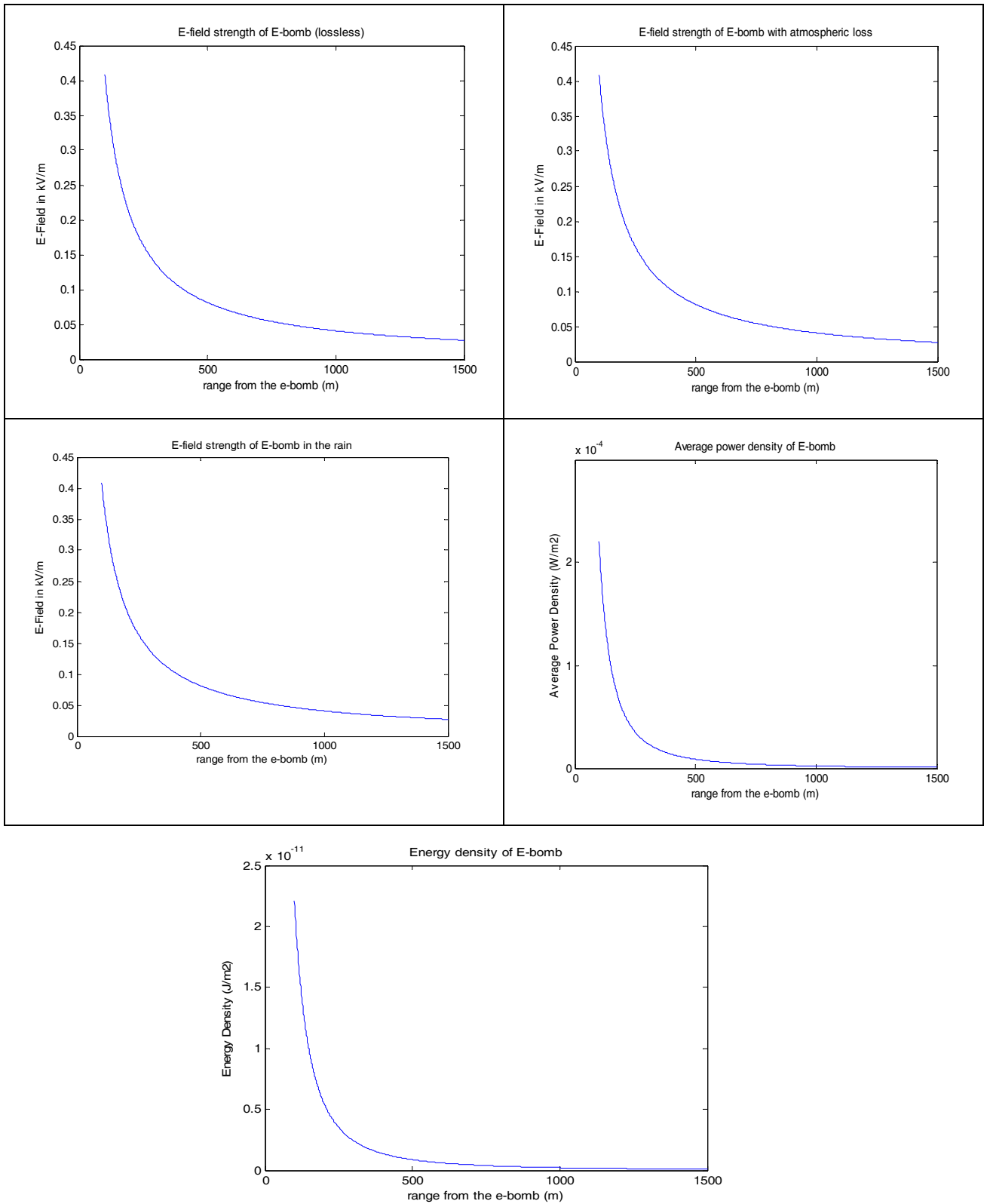


Figure 32. Simulation output for low-tech e-bomb

Upset levels as low as 15 V/m have been reported for the electronic control module in a public bus engine (Bäckström and Lövstrand, 2004). According to the referenced report, 15 V/m field strength caused an engine to stop. If considered as a threshold value for public bus engines, according to the simulation, the low-tech e-bomb model produces field strength that exceed the electromagnetic susceptibility limits of the cited public bus for ranges up to 2.7 km (see Figure 33). That means, the proposed low-tech e-bomb has a potential upset effect out to a range of 2716 meters as compared to the public bus data.

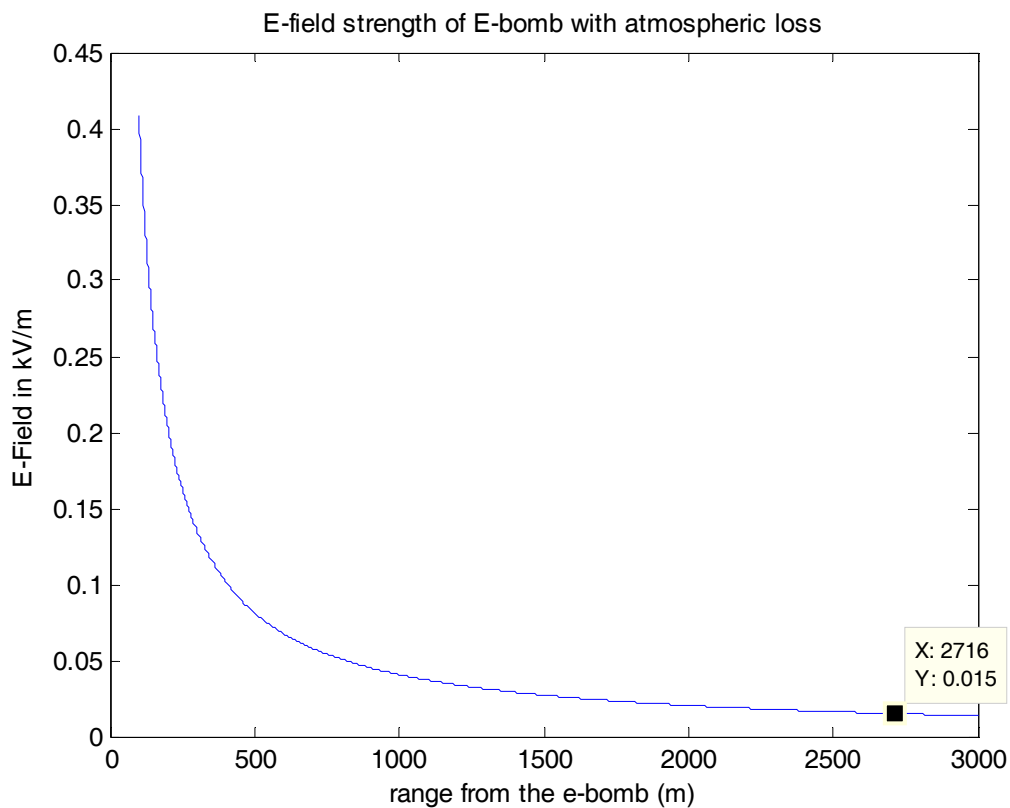


Figure 33. Low-tech E-bomb lethality range for public bus threshold level

Another upset threshold level as low as 30 V/m was reported for personal computers (PC) when 30 V/m field strength caused disruption and as a result computer had to be rebooted in order to gain operation (Bäckström and Lövstrand, 2004). If this level is considered as the upset threshold value for similar electronic to PCs, according to the simulation, the low-tech e-bomb

produces field strength that exceeds the electromagnetic susceptibility limits of PC up to 1.36 km away from the antenna (see Figure 34). That means, the proposed low-tech e-bomb has a potential upset effect range of 1359 meters against personal computers, or similar electronics. One can think that the new PCs are even more susceptible to microwave radiation than older ones. In this case, it is clear that the lethality range of e-bomb is even greater than 1.36 km against PCs.

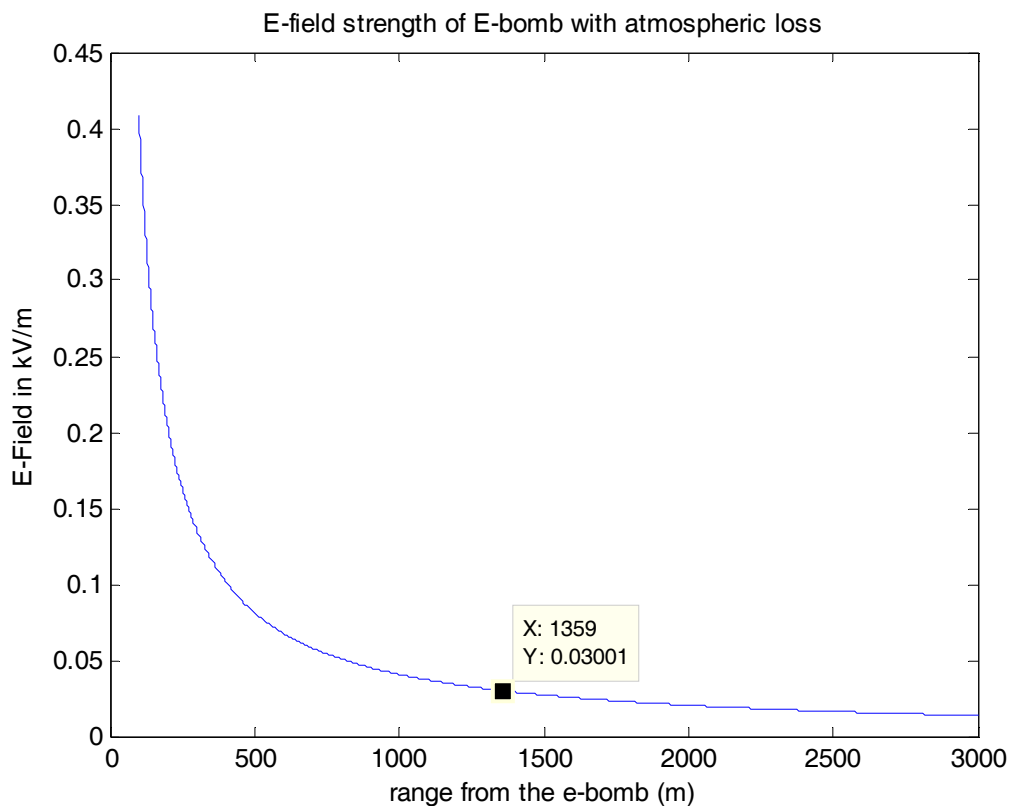


Figure 34. Low-tech E-bomb lethality range for personal computer

In the same article, permanent damage level for exposure to fields as low as 100 V/m is reported for PC flat screens (Bäckström, and Lövstrand, 2004). In this case, the low-tech e-bomb model produces field strengths that exceeds the electromagnetic susceptibility limits of PC flat screens threshold up to 400 meters (see Figure 35). That means, the proposed low-tech e-bomb has a potential lethality range of 407 meters against personal computer flat screens.

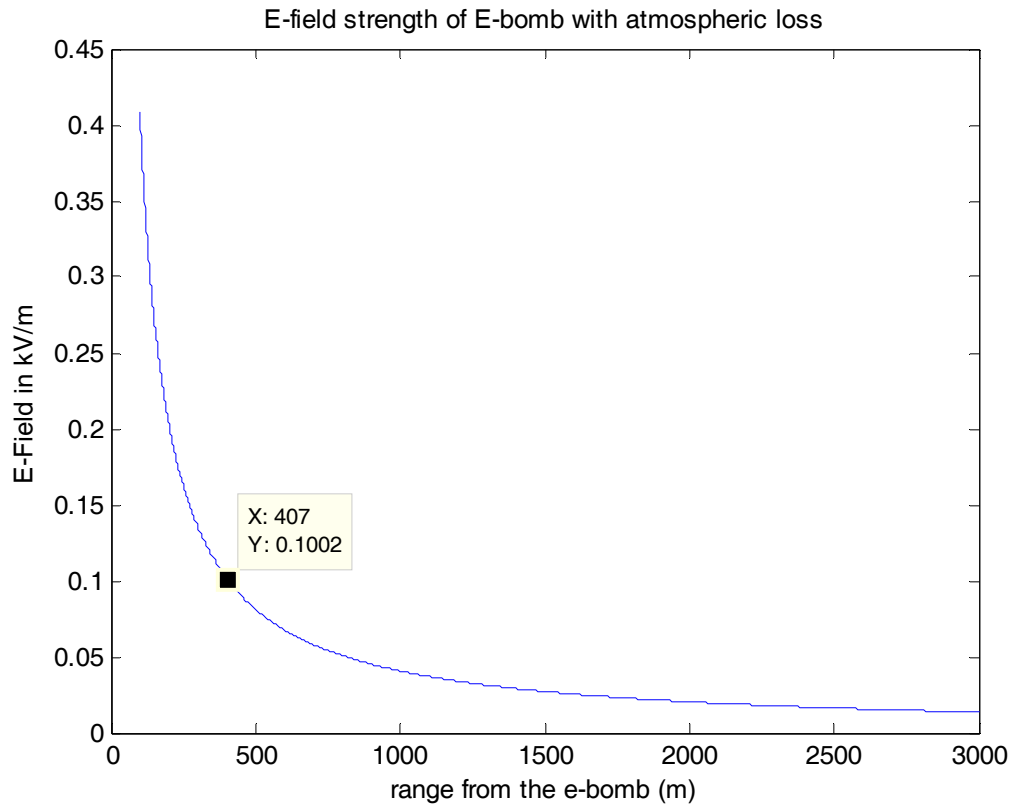


Figure 35. Low-tech E-bomb lethality range for personal computer flat screen

Finally, for the KIM-1 microprocessor, upset level as low as 2 V/m were reported (Taylor and Giri, 1994). For any electronic devices that involve KIM-1 microprocessor, the low-tech e-bomb model produces field strength that exceeds the electromagnetic susceptibility limits of KIM-1 microprocessor for all ranges up to 20 km (see Figure 36). That is, the proposed low-tech e-bomb has an upset threshold range of 20 km against the fully exposed electronic devices that involves KIM-1 microprocessors.

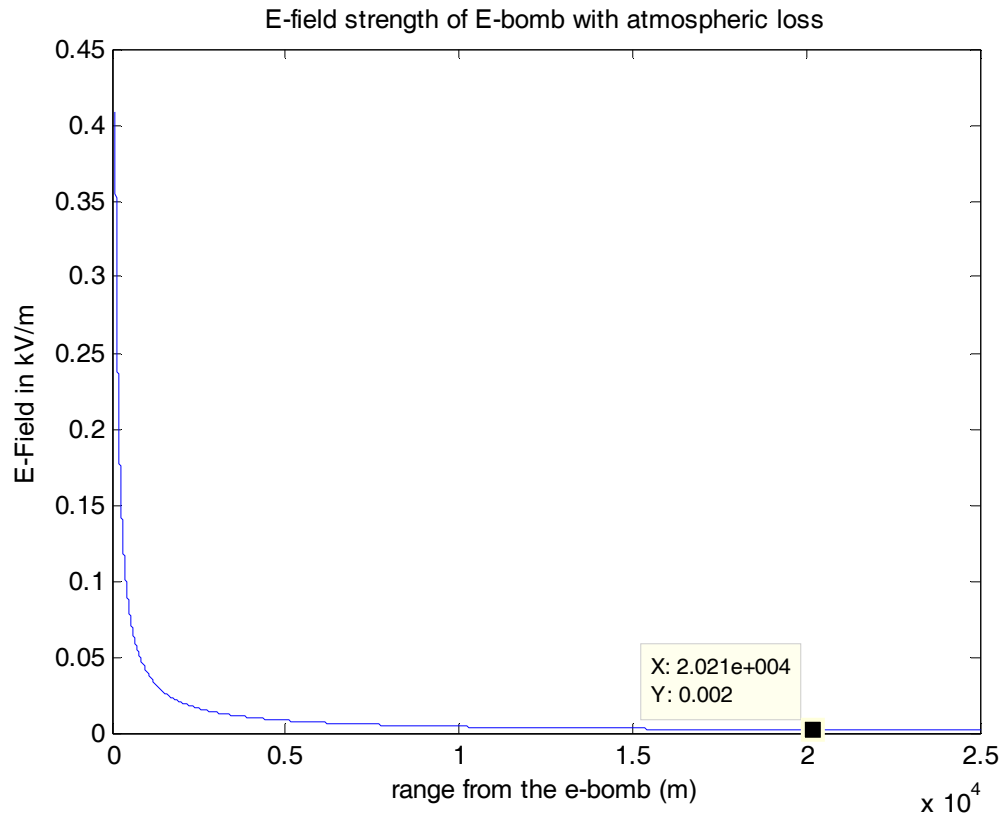


Figure 36. Low-tech E-bomb lethality range for KIM-1 microprocessor

2. Medium-Tech (Moderate) E-Bomb

The specifications for medium-tech (moderate) e-bomb are defined in Table 1. The medium tech simulation is run for two operating mode of e-bomb. The first mode has the operating frequency of 1.2 GHz and corresponding waveguide is WR770 ($a=0.19558$ m, $b=0.09779$ m). Table 11 shows the different output of the e-bomb in terms of different power levels between 1-20 MW.

P_{avg} (MW)	E_{max} (waveguide) (MV/m)	E_{peak} (at the aperture) (kV/m)	FOM (MV)
1	0.32	48.9	0.96
2	0.45	69.3	1.35
3	0.55	84.8	1.66
4	0.64	97.9	1.92
5	0.71	109.5	2.14
6	0.78	120.0	2.35
7	0.84	129.6	2.54
8	0.90	138.5	2.71
9	0.96	146.9	2.88
10	1.01	154.9	3.03
11	1.06	162.4	3.18
12	1.11	169.7	3.32
13	1.15	176.6	3.46
14	1.19	183.3	3.59
15	1.24	189.7	3.72
16	1.28	195.9	3.84
17	1.32	202.0	3.95
18	1.36	207.8	4.07
19	1.39	213.5	4.18
20	1.43	219.1	4.29

Table 11. Simulation output for field strengths of medium-tech e-bomb with WR770 waveguide

Proposed e-bomb produces 3.72 kV/m field strength at 1 km for 15 MW power level and 4.29 kV/m for 20 MW at the same point (see Table 12). Calculations do not include atmospheric losses.

P_{avg} (MW)	E r = 1m	E r = 1 km	E r = 5 km	E r = 10 km	E r = 100 km
15	3.72 MV/m	3.72 kV/m	744 V/m	372 V/m	37.2 V/m
20	4.29 MV/m	4.29 kV/m	858 V/m	429 V/m	42.9 V/m

Table 12. Field strengths of low-tech e-bomb at different ranges

The second mode has the operating frequency of 1.7 GHz and corresponding waveguide is WR650 ($a=0.1651$ m, $b=0.08255$ m). With the increased frequency and relatively smaller waveguide the strength of E-field produced by the medium-tech e-bomb increases about 60% (see Table 13).

P_{avg} (MW)	E_{max} (waveguide) (MV/m)	E_{peak} (at the aperture) (kV/m)	FOM (MV)
15	1.40	216.4	6.01
20	1.61	249.9	6.94

Table 13. Simulation output for field strengths of low-tech e-bomb with WR430 waveguide

Given that the e-bomb operating frequency is 1.7 GHz and is configured for two power levels, 15 MW and 20 MW, the produced field strength at 1 km from the e-bomb is 6.01 kV/m for 15 MW and 6.94 kV/m for 20 MW (see Table 14). Atmospheric losses are not included.

P_{avg} (MW)	E r = 1m	E r = 1 km	E r = 5 km	E r = 10 km	E r = 100 km
15	6.01 MV/m	6.01 kV/m	1.202 kV/m	601 V/m	60.1 V/m
20	6.94 MV/m	6.94 kV/m	1.388 kV/m	694 V/m	69.4 V/m

Table 14. Field strengths of low-tech e-bomb at different ranges

Among the different power levels, 20 MW source is chosen with WR650 waveguide in order to estimate the potential lethality range of the moderate e-bomb simulation for different types of targets.

Some of the simulation output for different parameters of the e-bomb is shown on Figure 37 (All simulation output for the medium-tech e-bomb is shown in Appendix-C). The results show that at 4 km, the atmospheric loss due to the moderate rain decreases the field strength by 1 V/m. Lossless E-field strength at 4 km from the e-bomb is 1.735 kV/m where E-field strength with atmospheric loss is 1.732 kV/m and E-field strength with atmospheric loss and rain loss is 1.731 kV/m at the same range.

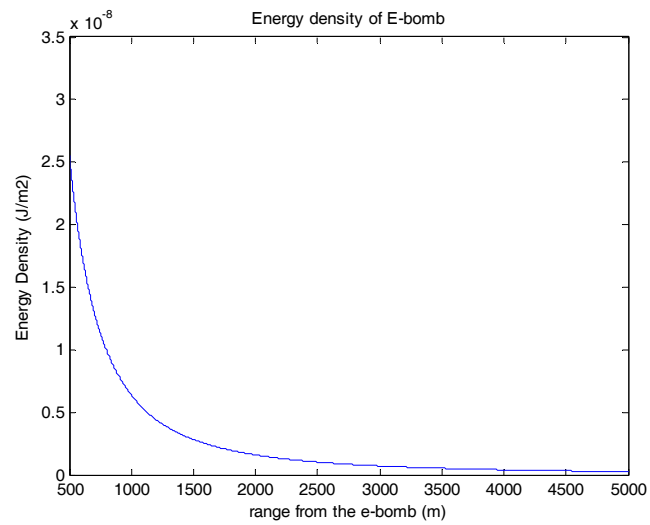
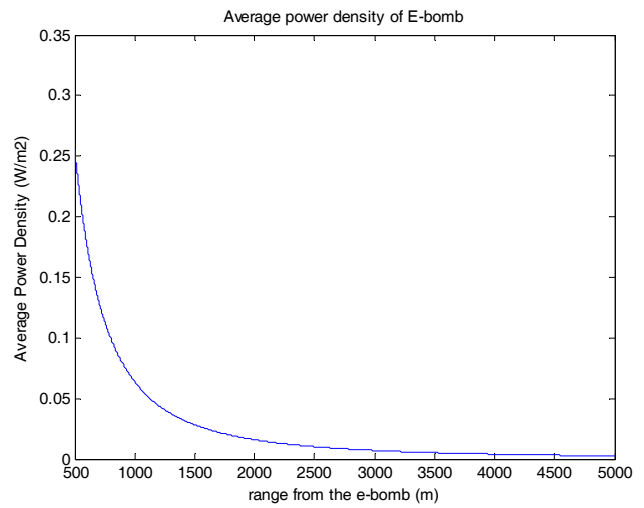
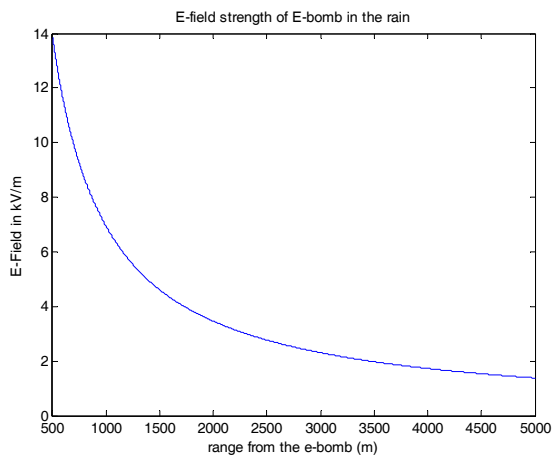
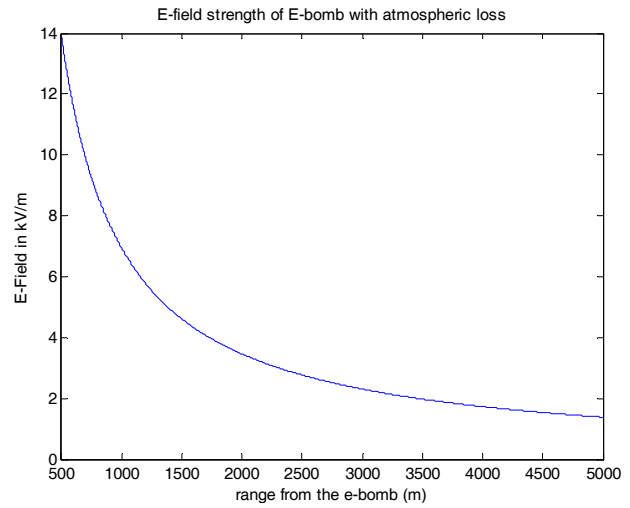
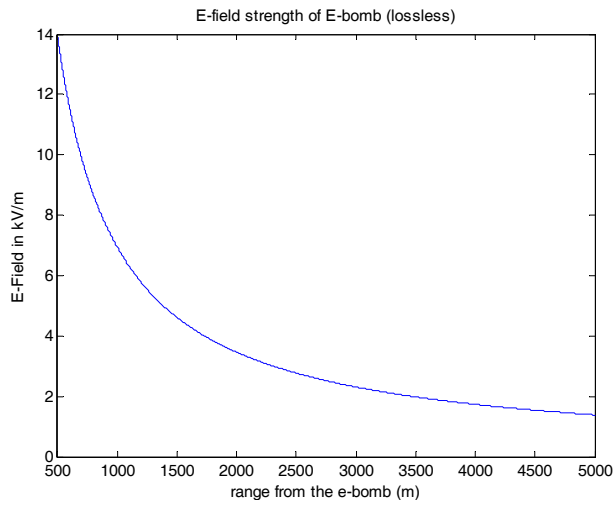


Figure 37. Simulation output for medium-tech e-bomb

In evaluating the outputs from the medium-tech e-bomb model, it will be appropriate to compare the radiated field strengths to the “design-to” standards for commercial aircraft (i.e., HIRF standards). As mentioned before, 30 dB shielding models commercial aircraft shielding effectiveness.

The HIRF standards shows that at the frequency range between 1-2 GHz, the maximum electric field strength environment in which the commercial airplanes fly is 3.3 kV/m (HIRF Standards, 2003). According to the simulation results, it can be concluded that the medium-tech e-bomb produces field strength that exceeds the HIRF standard limits of commercial airplanes up to a range from source of 2.1 km (see Figure 38). That is, the proposed medium-tech e-bomb has a potential lethality range of 2100 meters against commercial airplanes.

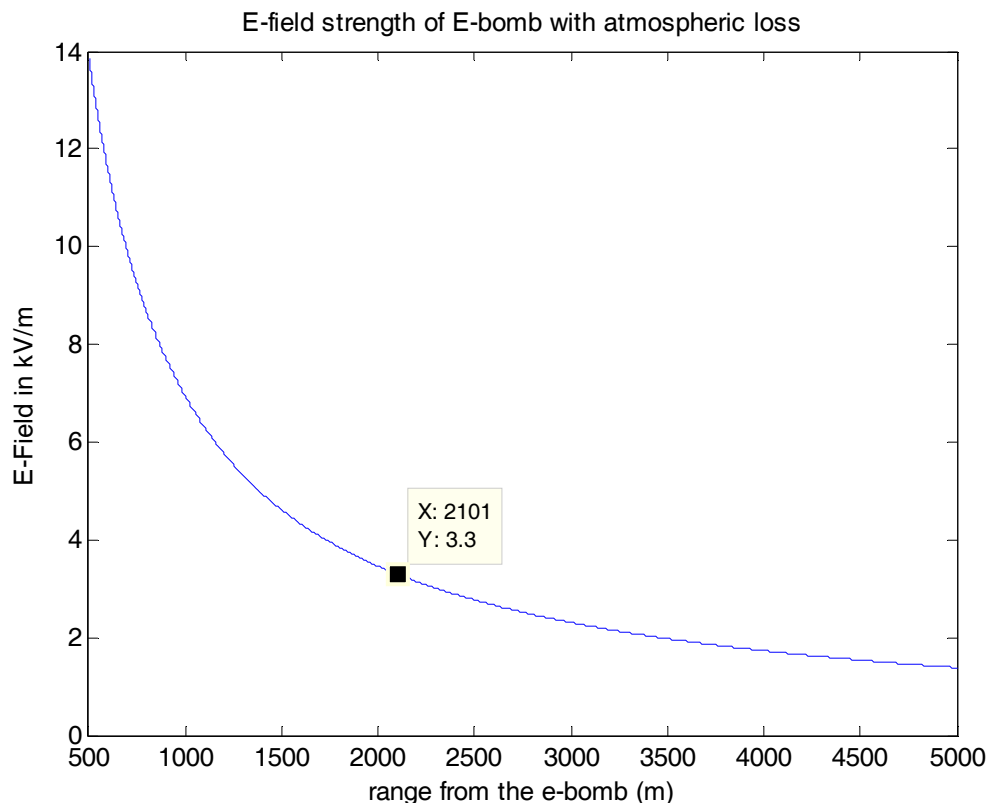


Figure 38. Medium-tech E-bomb lethality range for commercial airplanes

In the DNA report (*DNA EMP Awareness Course Notes*, Mindel, I. N. DNA Report No DNA2772T), it can be concluded that all known representative transistors, silicon-controlled rectifiers, diodes, and integrated circuits are susceptible to be damaged by 30 kW power level (Mendel, 1997). If this level is considered as a threshold value for any electronic system that includes one or more of those devices; according to the simulation, the medium-tech e-bomb delivers power into moderately shielded (30 dB) systems enough to exceed the electromagnetic susceptibility limits of those systems up to 2.3 km (see Figure 39). That is, the proposed medium-tech e-bomb has a potential lethality range of 2306 meters against moderately shielded systems.

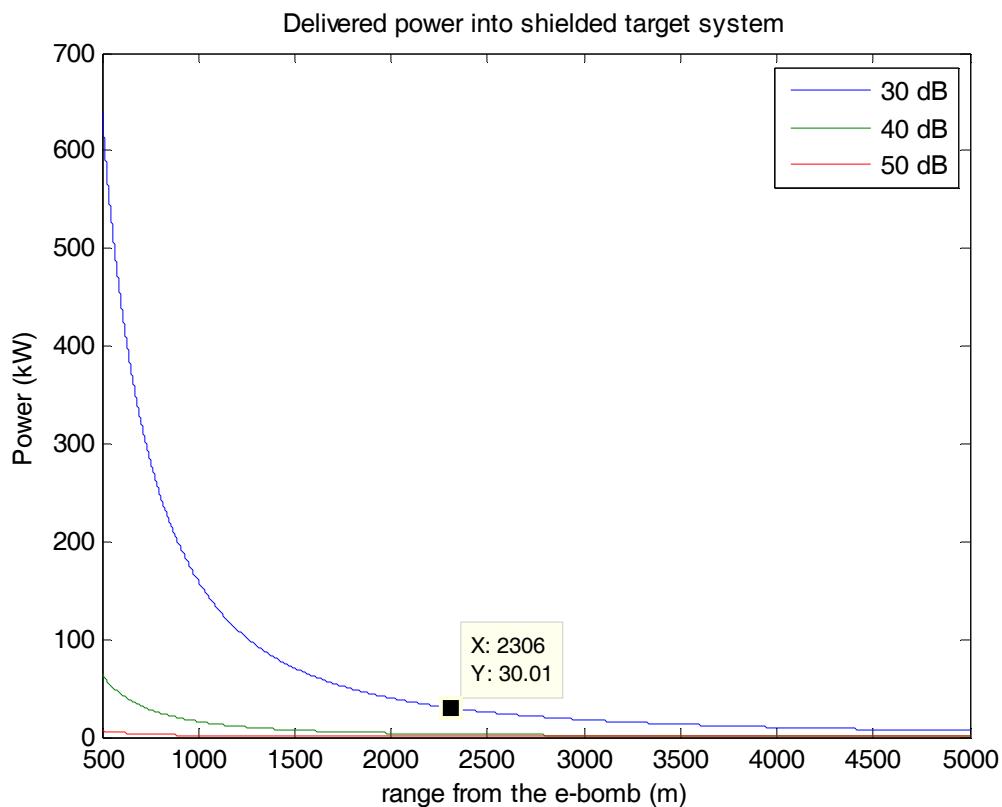


Figure 39. Medium-tech e-bomb potential lethality range for moderately shielded electronic systems

If the system is a 40 dB-shielded (fully shielded) military system, in this case, simulation results show that the medium-tech e-bomb produces power that exceeds the electromagnetic susceptibility limits of representative devices up to 730 meters (see Figure 40). That is, the proposed medium-tech e-bomb has a potential lethality range of 730 meters against 40 dB-shielded military systems.

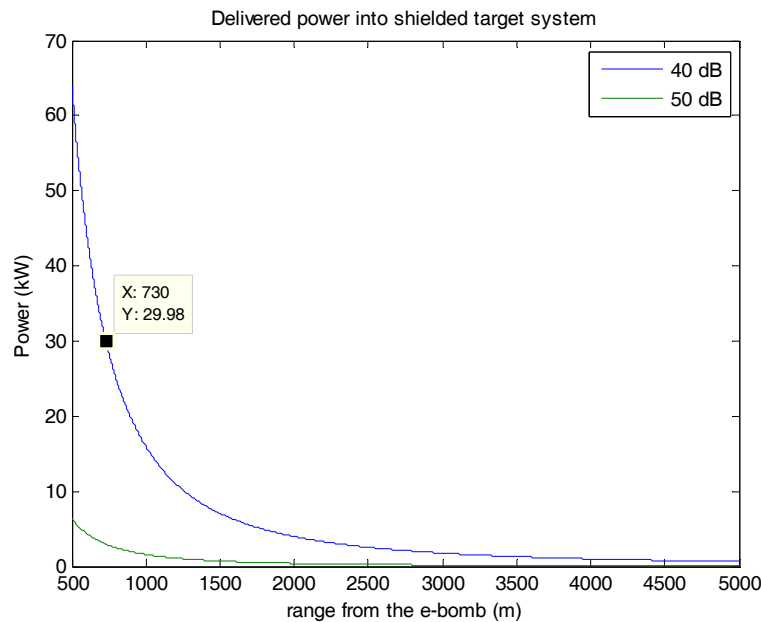


Figure 40. Medium-tech e-bomb potential lethality range for military systems (40 dB SE)

If the military system is shielded by 50 dB, the potential lethality range for permanent damage of the system then reduces to 231 m (see Figure 41).

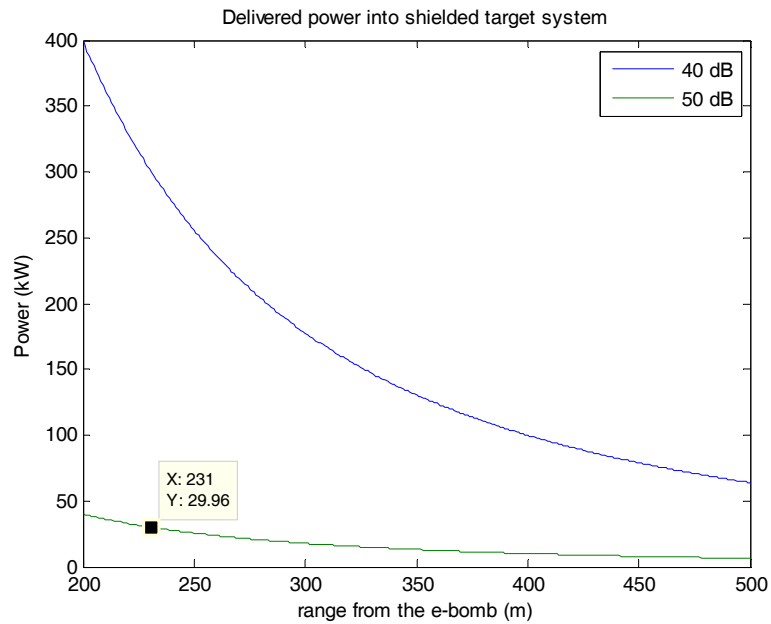


Figure 41. Medium-tech e-bomb potential lethality range for military systems (50 dB SE)

Recently, test results of HPM effects on Swedish Fighter Aircraft were published in open literature (Bäckström and Lövstrand, 2004). The test was conducted at microwave test facility (MTF) designed by the U.S. company TITAN Beta. Currently, the test facility is operated by Aerotech Telub for the systems owned by Swedish Defense Material Administration.



Figure 42. The Swedish MTF testing the HPM effects on Swedish Fighter Aircraft (Bäckström and Lövstrand, 2004)

The described test investigated susceptibility of the military systems to HPM. The results showed that upset began to occur around a few hundred volts per meter. On the other hand, the threshold level for permanent damage was reported at the field strength of 15-25 kV/m.

If the upset level for military systems is assumed 750 V/m according to the empirical data reported by Bäckström, and Lövstrand, it can be concluded that the potential upset range of proposed medium-tech e-bomb model against the military aircrafts is about 9.2 km (see Figure 43).

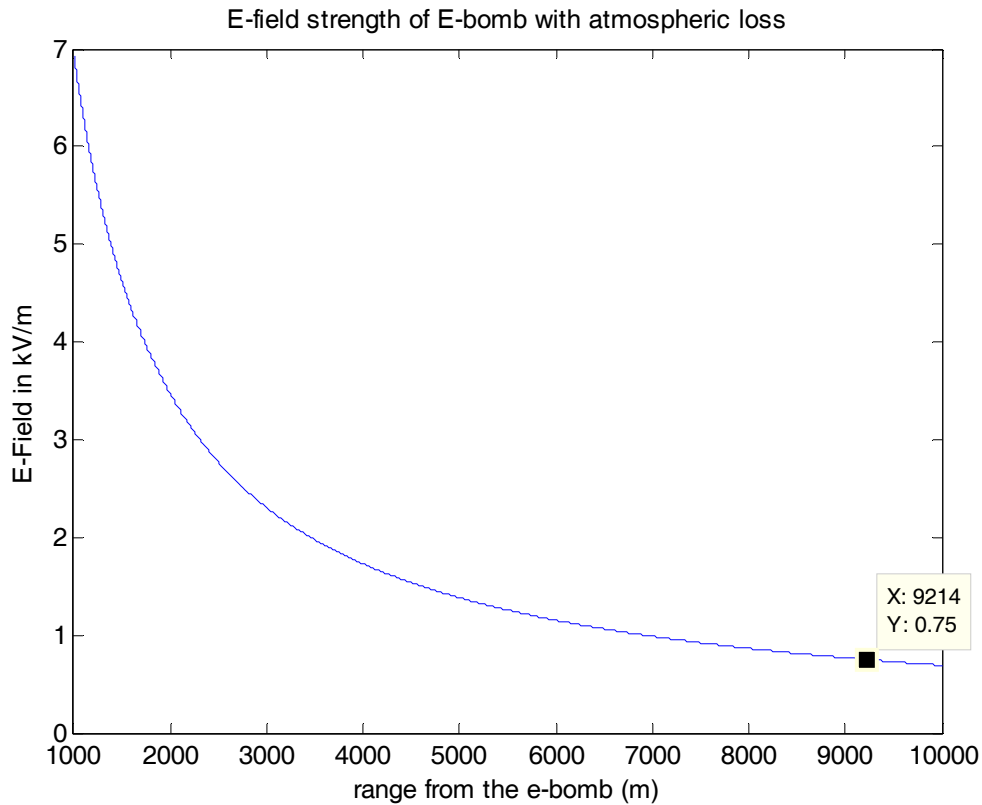


Figure 43. Medium-tech e-bomb potential upset range for Swedish Fighter Aircraft

From the empirical data in the Swedish fighter testing, 15 kV/m field strength was assumed as the threshold value of military aircrafts for permanent damage. Under this assumption, the output of the simulation shows that the medium-tech e-bomb model produces field strength that exceeds the electromagnetic susceptibility limits of Swedish Fighter Aircraft for ranges up to 463 m (see Figure 44).

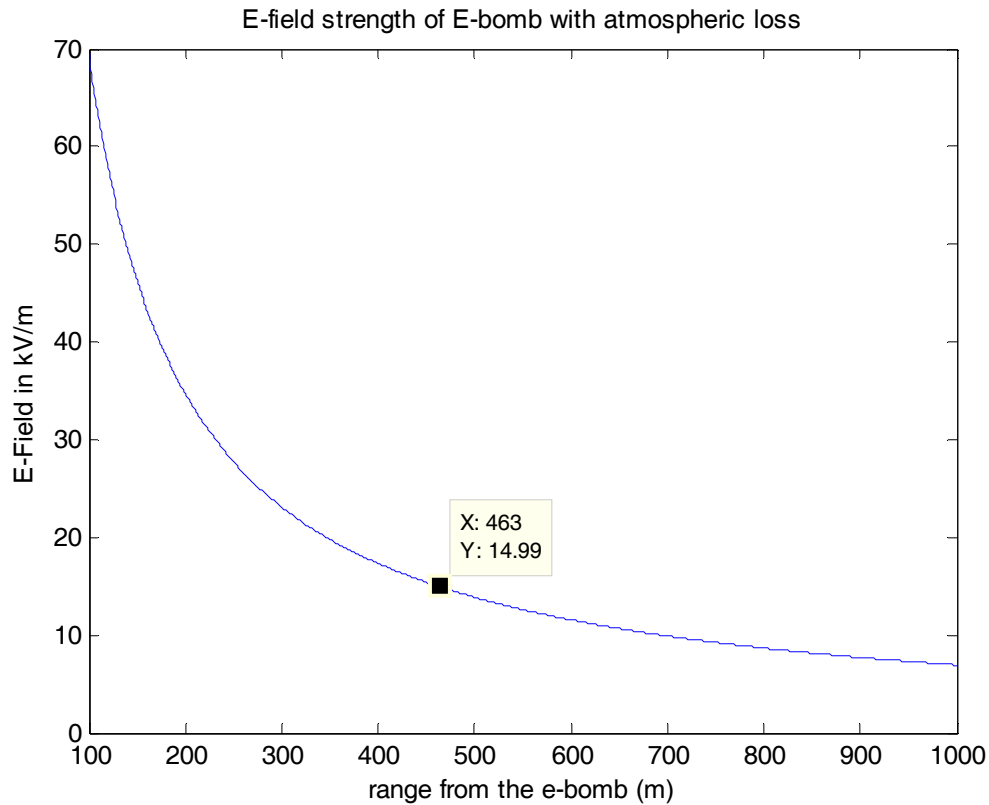


Figure 44. Medium-tech e-bomb potential lethality range for Swedish Fighter Aircraft

The comparison of simulation results of military systems for the stated assumptions and the empirical data are shown in Table 15. The output data shows that 40-50 dB shielding effectiveness assumption for military systems is valid since the output of assumed data is consistent with the empirical data.

Potential Lethality range for Permanent damage against 40 dB shielded military systems	Potential Lethality range for Permanent damage against Swedish Fighter Aircraft	Potential Lethality range for Permanent damage against 50 dB shielded military systems
730 m.	463 m.	231 m.

Table 15. Potential Lethality range comparison of military systems for moderate e-bomb

It has also been reported that the unshielded computers suffer bit errors when exposed to microwave fluence as low as $10^{-8} \mu\text{J}/\text{cm}^2$ ($= 10^{-10} \text{ J}/\text{m}^2$) through the back-door coupling (Florig, 1988). This threshold value can be compared to the energy density of the e-bomb model in the simulation. The simulation output shows that the medium-tech e-bomb produces energy density that exceeds the electromagnetic susceptibility limits of unshielded computers up to 8 km (see Figure 45). That is, the proposed medium-tech e-bomb has the potential upset range of 7963 m against the unshielded computer in terms of causing bit errors.

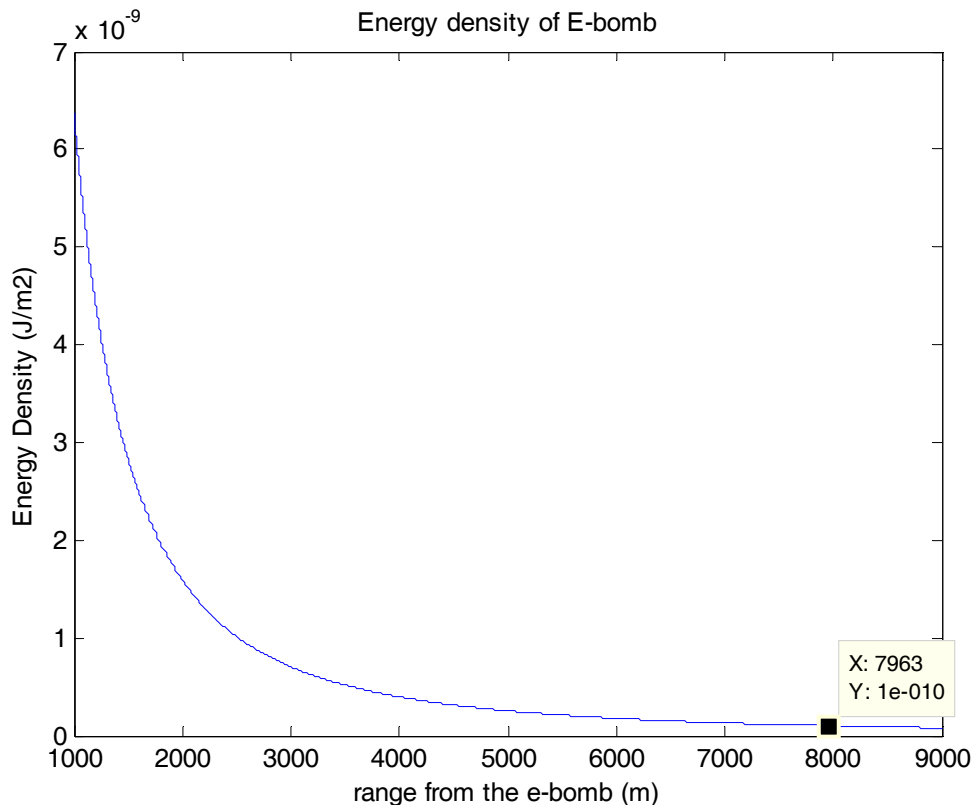


Figure 45. Medium-tech e-bomb potential upset range for unshielded computers

3. High-Tech (Powerful) E-Bomb

The specifications for high-tech (powerful) e-bomb are defined in Table 1. The proposed e-bomb now has 2 GHz operating frequency and corresponding waveguide is WR510. Table 16 shows the simulation output for the high-tech e-bomb.

P_{avg} (MW)	E_{max} (waveguide) (MV/m)	E_{peak} (at the aperture) (kV/m)	FOM (MV)
20	66.4	1.72	143.35

Table 16. Simulation output for field strengths of high-tech e-bomb

The results show that the produced field strength is 143.35 kV/m at 1 km from the e-bomb and 14.4 kV/m at 10 km (see Table 17). These estimates do not include atmospheric losses.

P_{avg} (MW)	E r = 1m	E r = 1 km	E r = 5 km	E r = 10 km	E r = 100 km
20	143.35 MV/m	143.35 kV/m	28.67 kV/m	14.335 kV/m	1.44 kV/m

Table 17. Field strengths of high-tech e-bomb at different ranges

Some of the simulation output for different parameters of the e-bomb is shown in Figure 46 (All simulation output for the high-tech e-bomb is shown in Appendix-C). The results show that at 9 km, the atmospheric loss due to the moderate rain decreases the field strength by 20 V/m. Lossless E-field strength at 9 km from the e-bomb is then 15.93 kV/m where E-field strength with atmospheric loss is 15.86 kV/m and E-field strength with atmospheric loss and rain loss is 15.84 kV/m at the same range.

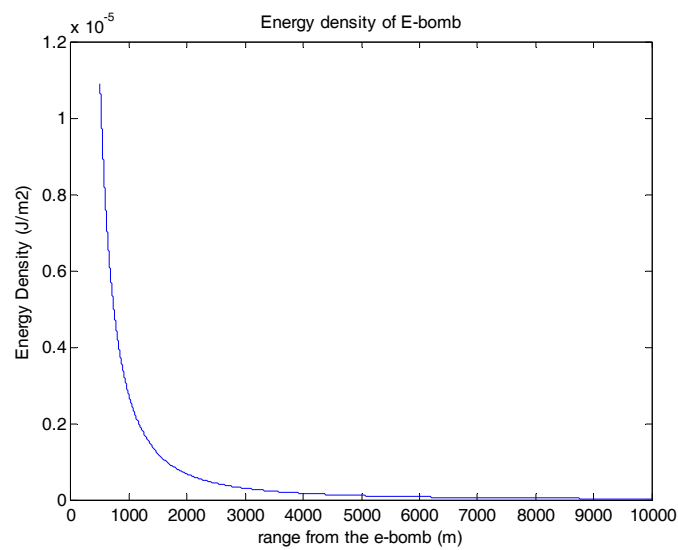
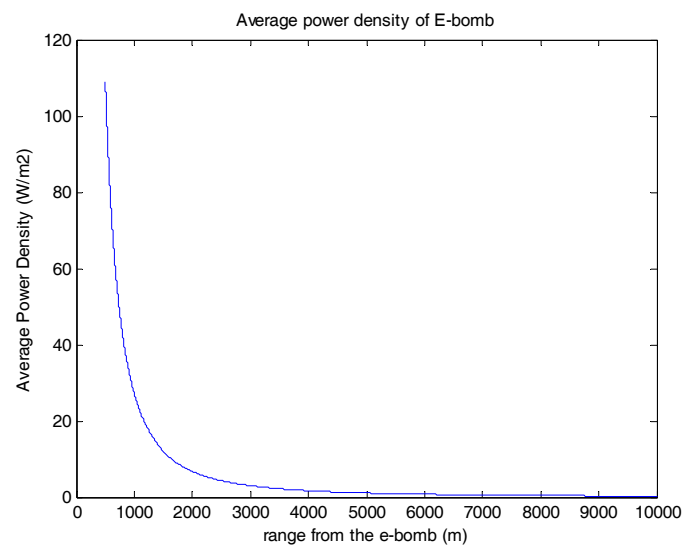
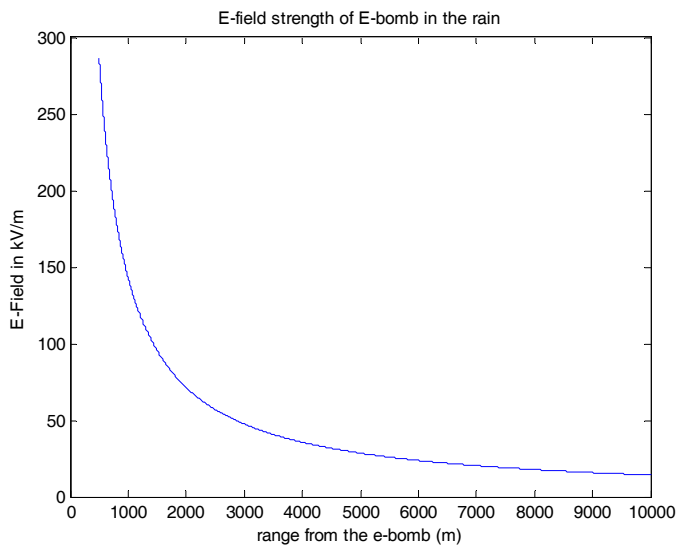
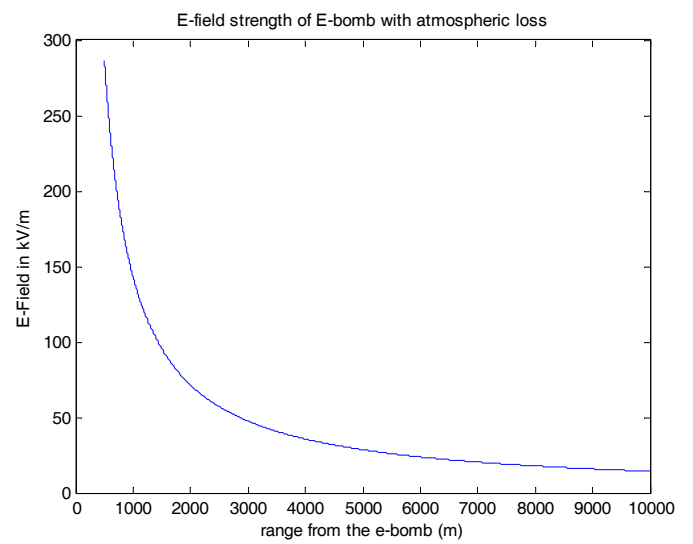
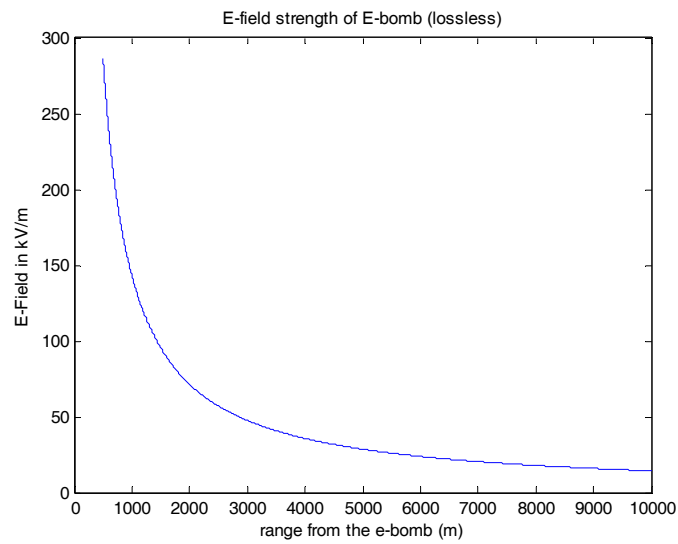


Figure 46. Simulation output for high-tech e-bomb

According to the HIRF standards, simulation results show that the high-tech e-bomb produces field strength that exceeds the standard environment limits of commercial airplanes up to 42.6 km (see Figure 47). That is, the proposed high-tech e-bomb has a potential lethality range of 42,590 meters against commercial airplanes.

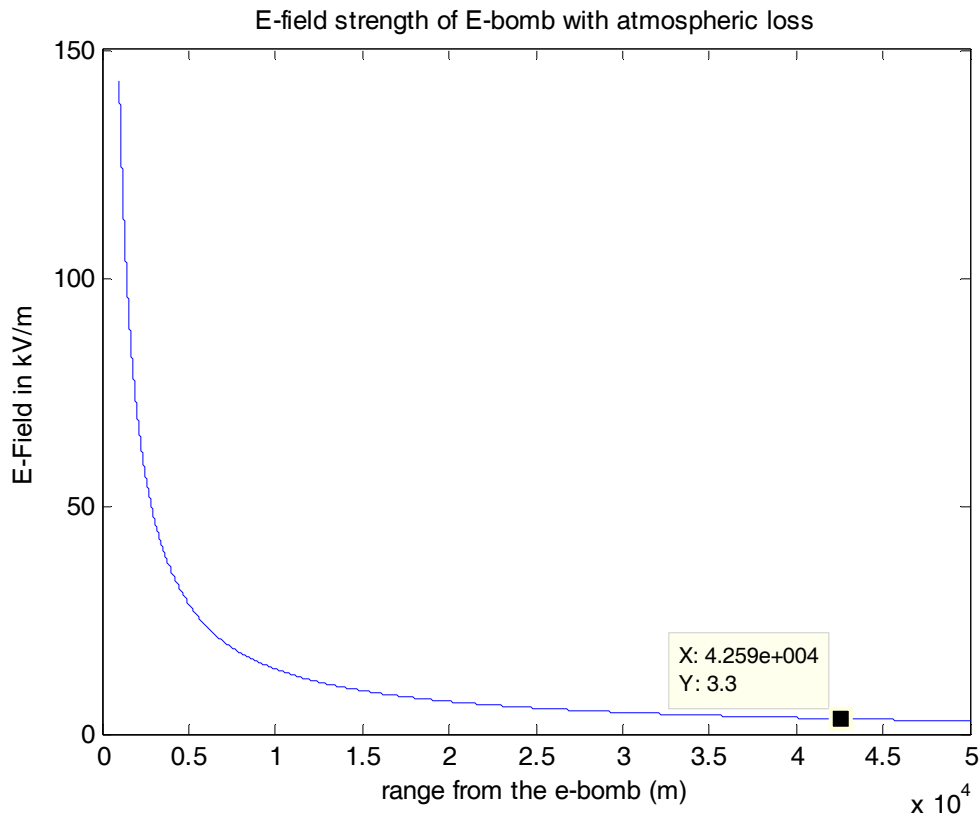


Figure 47. High-tech e-bomb potential lethality range for commercial airplanes

Simulation outputs shows that moderately shielded electronic systems are susceptible to the high-tech e-bomb up to 46.7 km (see Figure 48). That is, the proposed high-tech e-bomb has a potential lethality range of 46.67 km against moderately shielded systems.

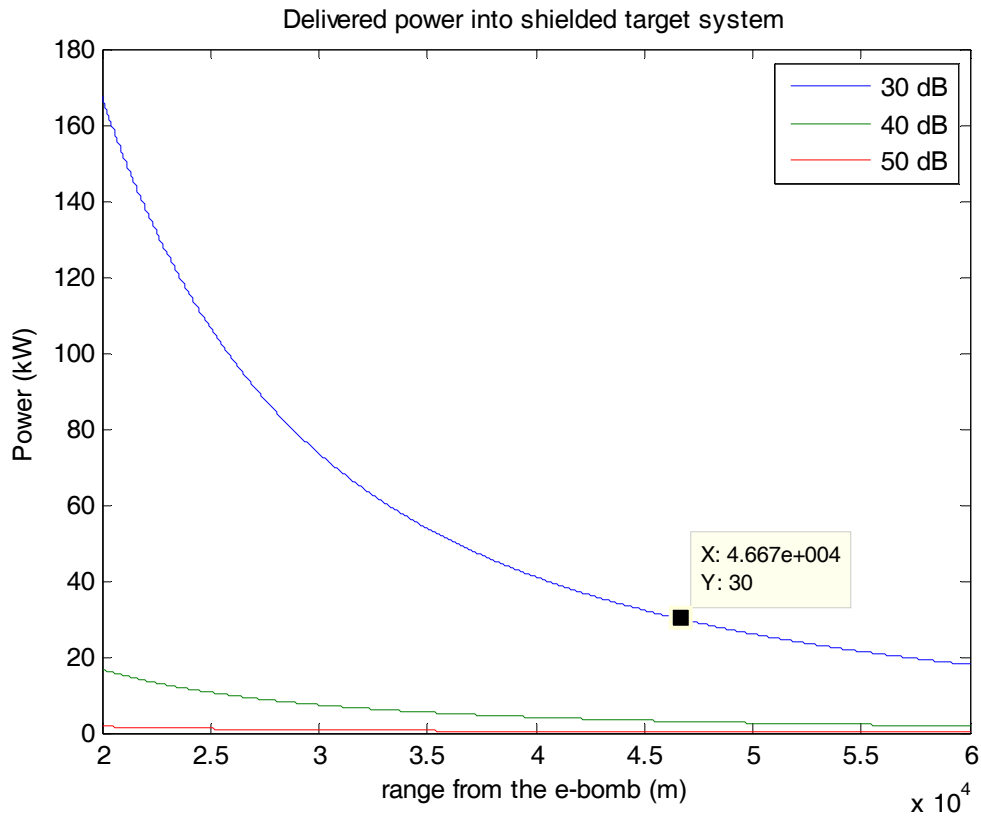


Figure 48. High-tech e-bomb potential lethality range for moderately shielded electronic systems (30 dB SE)

If the electronic equipment is a 40 dB-shielded (fully shielded) military system, in this case, simulation results show that the high-tech e-bomb produces power that exceeds the electromagnetic susceptibility limits of representative devices up to 15 km (see Figure 49). That is, the proposed high-tech e-bomb has a potential lethality range of 14.98 meters against 40 dB-shielded military systems.

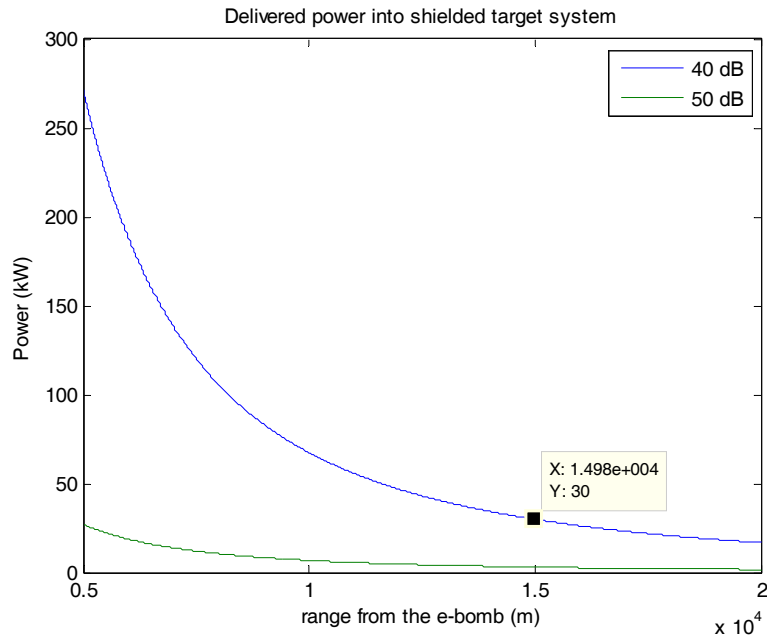


Figure 49. High-tech e-bomb potential lethality range for military systems (40 dB SE)

If the military system has 50 dB in shielding, the potential lethality range for permanent damage of the system then drops to 6.72 km (see Figure 50).

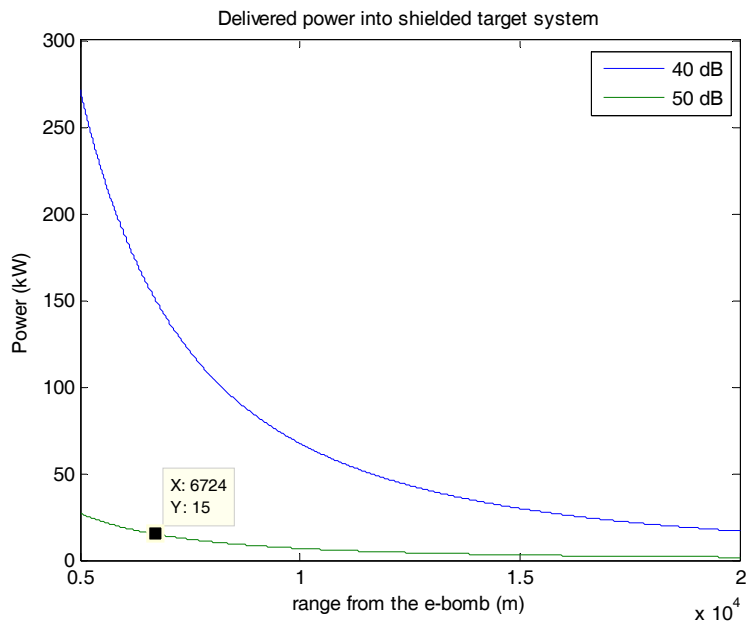


Figure 50. High-tech e-bomb potential lethality range for military systems (50 dB SE)

The high-tech e-bomb produces more than 15 kV/m field strength, which was the permanent damage threshold level for Swedish Fighter Aircraft, up to 9.5 km (see Figure 51), which means that the potential lethality range for e-bomb is 9,500 m.

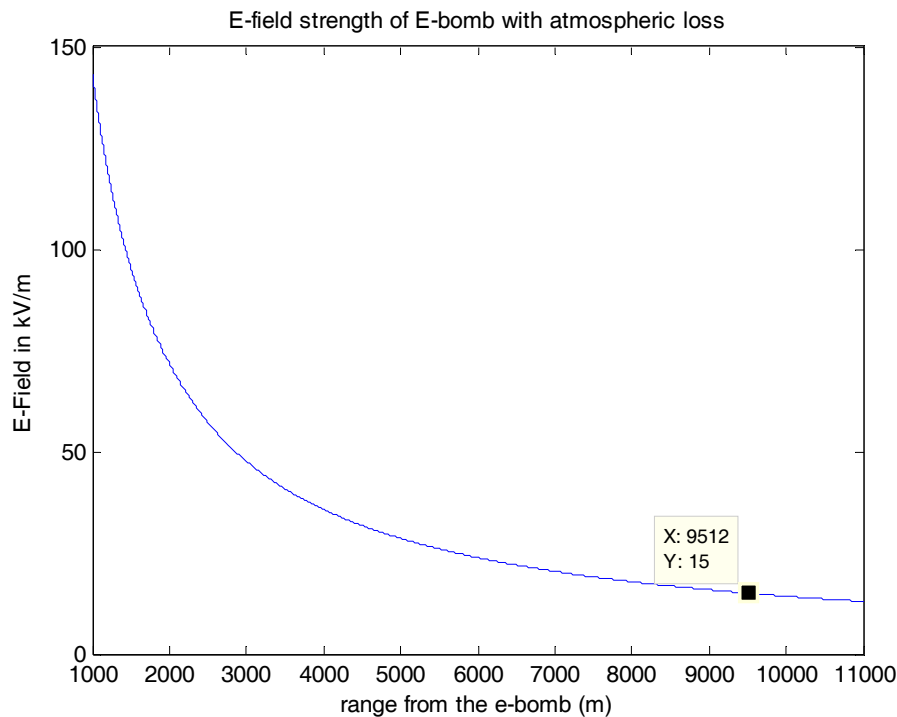


Figure 51. High-tech e-bomb potential lethality range for Swedish Fighter Aircraft

The comparisons of simulation results of military systems for the assumption data and the empirical data are shown in Table 18. The data again verifies the 40-50 dB shielding effectiveness is appropriate for military systems.

Potential Lethality range for Permanent damage against 40 dB shielded military systems	Potential Lethality range for Permanent damage against Swedish Fighter Aircraft	Potential Lethality range for Permanent damage against 50 dB shielded military systems
14980 m.	9512 m.	6724 m.

Table 18. Lethality range comparison of military systems for powerful e-bomb

Finally, according to the reported data, the simulation shows that the proposed high-tech e-bomb has a potential upset range of 153.8 km against the unshielded computer in terms of causing bit errors (see Figure 52).

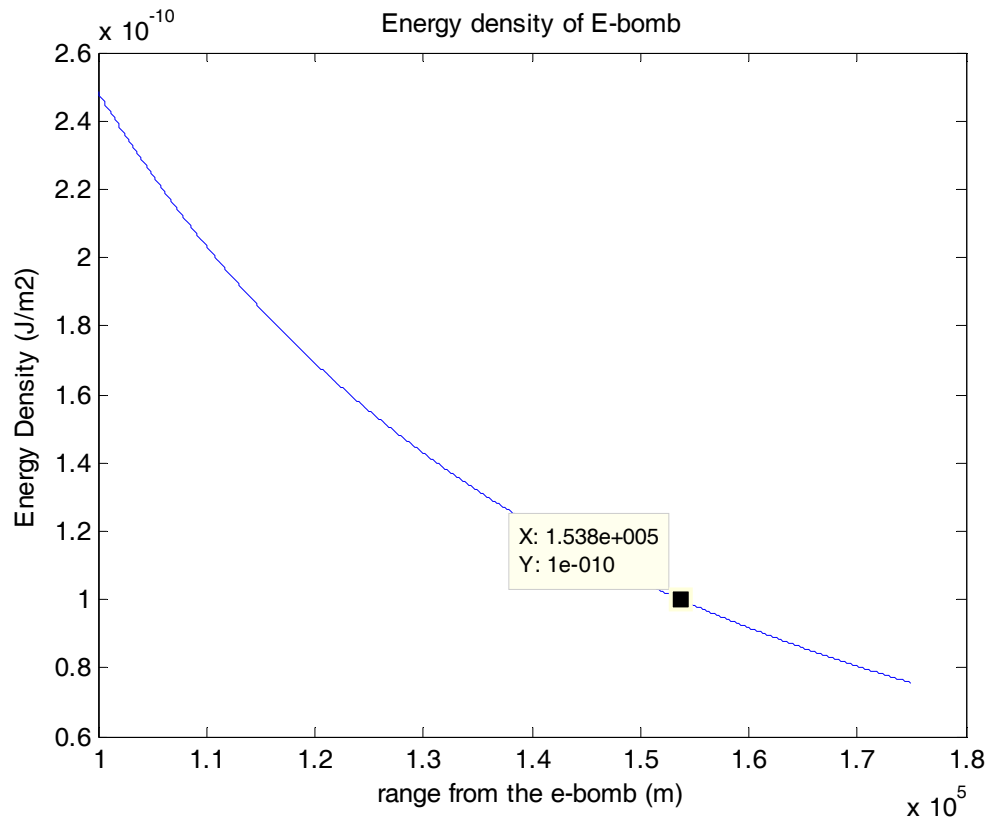


Figure 52. High-tech e-bomb potential upset range for unshielded computers

G. DEFENSE AGAINST E-BOMB

The possible effect of an e-bomb could be upset or permanently damage on electronic devices within the lethality range. Even though the electronic device is turned off, there is still a high possibility that the device could be detrimentally affected.

The fact that the best protection against any weapon is destroying the platform on which the weapon is delivered, is also valid for e-bombs. But sometimes this solution can not be easily implemented or even possible.

In this case, the best protection against e-bombs seems to be hardening the electronic equipment against microwave radiation.

From the defense perspective, in the event of a war, e-bombs could be the first kind of weapons to be used against communication systems and air defense systems. In such a case, it is vital to prepare by hardening in advance all the defensive countermeasures before the attack.

The most effective method for shielding is to wholly contain the equipment in an electrically conductive enclosure, termed a Faraday cage, which prevents the electromagnetic field from gaining access to the protected equipment (Kopp, 1993). But even in this case, since most such equipment must be fed with power from the outside world, the penetrations, the cracks, the seams, etc, create a vulnerability at the entry points against an electromagnetic environment such as from e-bombs.

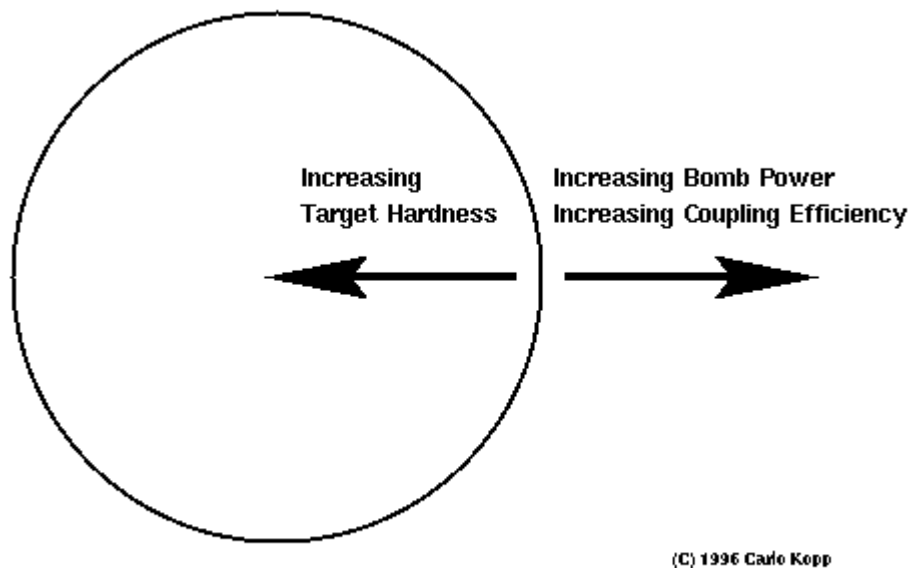


FIG.5.1 E-BOMB LETHAL RADIUS

Figure 53. Shielding Effect against e-bomb (Kopp, 1996)

Figure 53 shows the effect of shielding the electronic devices. If the shielding effectiveness is increased to a level at which the e-bomb lethality range does not make sense anymore, use of e-bomb would cease to be a good option for the opponent. The counter attack for the shielding is increasing the power of the e-bomb source. At some point, however, the breakdown in the atmosphere will be a limiting factor for the design of such a high power source-e-bomb.

The technology for protection from high-power microwave energy through topological shielding with terminal protection devices and filter isolation is available. It can be used to provide adequate hardening for any level of exposure. However, as the incident fluence is increased, the degree of required protection becomes more difficult to achieve (Taylor and Giri, 1994).

As shown in the previous sections, even though a 50 dB shielding effectiveness is achieved, there could still be a threat for the electronic devices from e-bomb. More shielding effectiveness (i.e., 60, 70 dB) will obviously provide a better protection. On the other hand, it may not be possible to retrofit harden old systems up to this level. They may require a complete replacement. In simple terms, hardening by design in the system acquisition phase would be easier and cheaper and more effective than attempting to harden the existing device (Kopp, 1993). Even in this case, sometimes the entire topological shielding concept could not be a cost-effective approach. Hardening most military systems and mass-produces commercial equipment including PCs and communications equipment against HPM would add somewhere between from 3% to 10% to the total cost, if hardening is engineered into the original design. To retro-fit existing military electrical equipment with hardening would add about 10% to the total cost (Wood, 1999).

Other than shielding, passive electronic counter measures such as using low probability of intercept (LPI) techniques could be a good way to protect the systems. New LPI radar technology is a good example for these measures. If it can be achieved to hide the radar emissions from the enemy, there would not be any observable target for enemy to launch an e-bomb to attack.

Another technique could be to choose an appropriate topology for communications networks. In network centric warfare, the ratio of the capability of the communication network for all nodes to that of the reference network is called network richness (Pace, 2007). The network richness for a network is given by

$$I_R = \frac{1}{C_M^R} \sum_{\mu=1}^{N_T} K_{\mu} \sum_{v=1}^{N_{\mu}} L^{\mu v} \left(\sum_{\gamma=1}^{N_{\mu v}} \frac{F_{\gamma}^{\mu v}}{d_{\gamma}} \right) \quad (20)$$

where

- C_M^R : Reference network connectivity measure
- N_T : # of node
- K_{μ} : node μ capability value ($0 < K < 1$)
- N_{μ} : # of nodes connected to the node μ
- $L^{\mu v}$: information flow parameter of route γ connecting node μ, v
(($0 < L < 1$))
- $N_{\mu v}$: # of routes connecting pair of nodes μ, v
- $F_{\gamma}^{\mu v}$: connection capacity of route γ connecting node μ, v (F is either 0 or 1)
- d_{γ} : # of links of route γ connecting node μ, v .

According to equation (20), maximum value of network richness can be 1 where all nodes are connected to each other and all links and nodes have maximum capability. A better interactive network topology could be chosen as protection against e-bomb attack in order to maintain the operability of the network even though some portion of the network may be permanently damaged

after the e-bomb attack. The concept here is that the network would self-heal by re-routing mission critical information to more robust paths.

H. MILITARY UTILITY

Within this study, three types of hypothetical e-bomb have been proposed. Such an immature weapon concept will definitely have disadvantages in design and application phases. However, the foreseen advantages, as seen in the simulation results, make it attractive to put more effort in exploring the military utility of such a weapon.

1. Advantages

If the e-bomb can be produced, it will definitely be a key element of Electronic Warfare (EW). Electronic Attack, one of 3 divisions of EW, involves the use of electromagnetic or directed energy to attack personnel, facilities or equipment with the intent of degrading (Scleher, 1999). It is shown in the previous sections that such a weapon can most likely produce power outputs that exceed the known susceptibility levels of most of electronic devices, even if they are shielded. If it can be used as intended in the battlefield, e-bombs can potentially permanently damage opponent's electronic equipment. Or opponent's systems can be upset as a result of e-bomb attack, which gives a reasonable time for other assets to attack the enemy forces.

If the enemy is mostly dependent on a network to maintain command, control, communication, computer, intelligence, surveillance and reconnaissance (C4ISR), an e-bomb attack can probably degrade network functionality. Since the new generation battlefield concentrates on network centric warfare, one could say with confidence that an e-bomb will be an important threat to C4ISR for the future battlefield.

Another advantage of using e-bomb is the multiple effects on enemy systems. The first phase of the air war includes suppression of enemy air defense (SEAD) systems. Anti-radiation missiles (ARM) are universally accepted

weapons in order to accomplish SEAD missions. By comparison, one e-bomb can degrade multiple systems of diverse types whereas the ARM is used against only one system. When considering the cost/benefit issue of such missiles, the e-bomb can be an attractive weapon in comparison of ARM.

Outside the battlefield, there are several industries and institutions that support the armed forces such as companies producing defense products, TV stations broadcasting anti-propagation programs etc. If these support organizations are considered as viable military targets, and if it is considered that such buildings are moderately shielded, the e-bomb lethality against these targets will be much higher than that achieved against military targets.

Another major advantage for the e-bomb is that it can be delivered from any platform with a navigation-attack system capable of delivering GPS guided munitions. As we can expect GPS guided munitions to be the standard weapons for almost every platform for the foreseeable future, every platform can deliver e-bombs. It also gives an advantage to multi-role platforms.

2. Disadvantages

The potential lethality range of e-bomb mostly depends on the coupling efficiency of electric field strength into the target system. Since the coupling is a complex issue and has many parameters, a desirable lethality range can be reliable with accurate intelligence of opponent's system design and protection features. Such information is very difficult to obtain. That is why e-bomb damage assessment is an area that still needs improvement.

You will never know precisely how effective the e-bomb devastated the system. Even though the damage assessment does not seem possible to decide whether a soft kill or a hard kill is achieved; some methods can help to evaluate the result of e-bomb attack. Consider that the e-bomb is used against an enemy radar. If the e-bomb damaged the target radar, the enemy radar will stop transmitting for a long period unless an emission silence has been ordered at

that time. That is the result of passive electronic support systems operated to assess the electronic activity of the enemy's emitters could give an idea whether the e-bomb devastated the system or not. One can say, the e-bomb attack is successful, if the end result was that there is no electronic activity after the attack where there was before the attack.

In the context of targeting military equipment, it must be noted that thermionic technology (i.e., vacuum tube equipment) is substantially more resilient to the electromagnetic weapons effects than solid state (i.e., transistor) technology. Therefore a weapon optimized to destroy solid state computers and receivers may cause little or no damage to a thermionic technology device. Therefore a hard electrical kill may not be achieved against such targets unless a suitable weapon is used. (Kopp, 1993).

Another limitation of designing the e-bomb is the atmospheric limitation. In order to overwhelm this limitation, the waveguide and the reflector can be vacuumed and filled with appropriate gas to increase the breakdown limitation. In application, high breakdown limits such as 100 MV/m do not seem realistic. This is a big barrier to the technological improvement of such weapons.

The antenna is also a limiting factor for e-bombs. More effective range depends on the aperture size of the reflector. Since a big antenna is not appropriate in terms of delivering e-bombs to long distances, improvements in this area need to be achieved in the future. Arraying antennas might be worth investigating.

The accuracy of delivery can be another disadvantage for e-bombs. Our notional high-tech e-bomb has a potential upset range up to 15 km against military systems. If the e-bomb cannot be delivered to the intended point in the battlefield, it will obviously decrease effects considerably.

A notional low-tech (small) e-bomb has been introduced to show that it is easily designed with commercially available devices and does not require high level engineering experience. Moreover, that low-tech e-bomb is shown to produce power output more than the susceptibility level of unshielded systems up

to 3 km. Many electronic systems don't have any shielding. Terrorists can produce such weapons easily for use against civilian systems. It can lead to temporary panic in daily life.

The possibility that enemies or terrorists will have such weapons indicates the advisability of shielding our own assets. This necessity will increase production and maintenance cost of such systems.

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IV. COMPARISON OF WEAPONS BY USING MULTIPLE OBJECTIVE DECISION MAKING

No matter how rich and prosperous, a nation without independence, cannot be subject to any behavior before the humanity, at a higher level than serving.

— Mustafa Kemal Atatürk

After all the information proposed in the previous chapters, is it worthwhile to invest in research and development of an e-bomb? Even if such a weapon can be produced, is it really as lethal as other electromagnetic weapons? What would make proposed e-bombs attractive in comparison with other weapons? All these questions can be addressed using the method of Multi-Objective Decision Making.

Utilizing the information presented in the previous chapters, formulation for the comparison among the three types of weapons (the HEMP, the HPM, and the e-bomb) is detailed in this chapter. In order to do this, multi-objective decision analysis are used to assess the three types of weapons.

This chapter proceeds as follows: some basic principles are defined to introduce Multi-Objective Decision Making; a model is proposed in order to compare electromagnetic weapons; and the output is analyzed.

A. MULTIPLE OBJECTIVE DECISION

Decision making is defined in the open literature as:

Decision making is the process of selecting a possible course of action from all the available alternatives. In almost all such problems multiplicity of criteria for assessing alternatives is pervasive. That is, for many such problems, the decision-maker wants to attain more than one objective or goal while satisfying the constraints dictated by environment, processes, and resources. Another characteristic of these problems is that the objectives are frequently appear to be non-commensurable (Hwang and Masud, 1979).

Since the early 1960s, a large and diverse literature has been published in order to solve the multiple-objective decision problems that occurs because of the complexity of diverse situations and the multiplicity of factors that are involved. Theoretical and methodological developments have been based on a number of different opinions, reflecting the breadth of disciplines involved (Chankong and Haimes, 1983).

Multi-objective decision making involves an entire process of problem solving. A lucid description of the corresponding decision situation that defines the problem structure and the decision environment of the decision problem is a fundamental to a multi-objective decision problem. Such description can be accomplished by identifying the boundaries and the basic components of the problem. If the multi-objective decision process and the decision situation is considered as a black box, structurally, there will be some input information, and a process that is defined by the decision maker. As a result, a decision will be produced as output (Chankong and Haimes, 1983).

One way to make a multi-objective decision is to estimate the overall measure of effectiveness of each alternative. The approach of measure of effectiveness of any system depends on five key components: The decision-maker, a set of alternatives (course of actions), the environment in which the alternatives are shaped, a set of objectives and a set of decision rule. The flow diagram of this process is shown in Figure 54. According to the output of this process, some alternatives come better than others depending on the preferences of the decision maker.

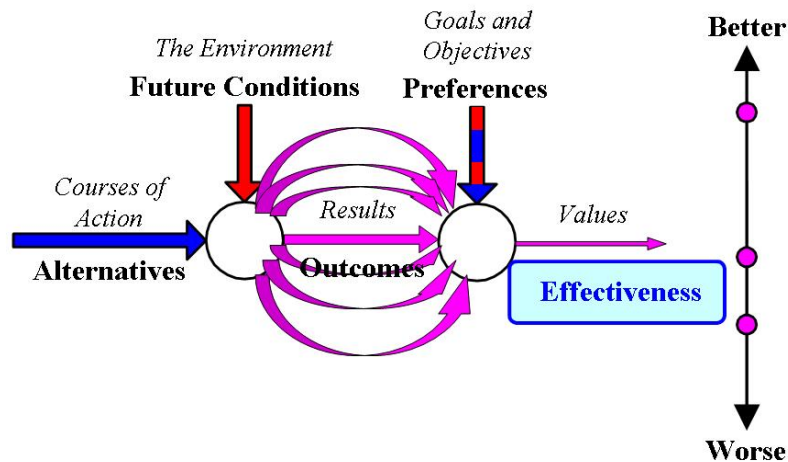


Figure 54. Measure of Effectiveness Model (Airola, 2007)

After defining the alternatives and the battle scenario (environment), the key step in evaluating each alternative is to define the objectives that are to be measured. The most common method to define the objectives and related sub-objectives is additive value model. Overall measure of effectiveness can be expressed in “additive value model.” This model defines the objectives in a hierarchical structure in which the relevant objectives are grouped as a set of objectives. Objectives at the lower level in the hierarchical structure are more specific and more operational than those at the higher level. That is, the objectives at the lowest level of the hierarchy are the most specific and the most operational objectives overall (Chankong and Haimes, 1983).

For multiple objective decision making, structuring the objective hierarchy is the most important step. Objective hierarchy permits you to go from multiple objectives to a single measure of effectiveness (Airola, 2007).

An objective defined in the structure gets operational if the level of achieving such an objective can be assessed in a practical way. To make the objective operational, each objective is defined in terms of a group of attributes in the lowest level. An attribute is a measurable quantity whose measured value

reflects the degree of achievement for a particular objective. An attribute can be measured in quantity even though the achievement is defined in qualitative terms (Chankong and Haimes, 1983). The relation between an objective and an attribute is defined in open literature:

In many instances, the value of an attribute will give an obvious and direct indication of the degree of achieving an associated objective. These are called the proxy attributes. For example, the attribute “net profit” measured in terms of dollars is a direct measurement of the degree of achieving the objective “maximizing profit.” For some problems, it may be possible to formulate accurately the multi-objective decision problem in such a way that objectives and attributes are related only by direct relationships. This type of direct relationship between objectives and attributes is, indeed, what we would like to have. The idea of articulating objectives into hierarchical levels is, in fact, a way of achieving this goal. For each objective in the lowest level there should ideally exist an attribute or a set of attributes whose value is a direct measurement of the level of achieving that objective (Chankong and Haimes, 1983).

Proxy attributes are operationally measurable and assessable. They are also controllable. That is, whatever the decision-maker does, it affects the attributes. Another property of attributes is to be mutually exclusive, in order to avoid double counting.

Once the hierarchical structure is designed, the next step is to define the model mathematically. In this case I will use an additive value model where the value of the model depends on the added value of each objective/attribute and the assigned weight of the objective/attribute. The additive value model is expressed mathematically as

$$v(A) = w_1 v_1(A_1) + w_2 v_2(A_2) + \dots \quad (21)$$

where $v(A)$ is alternative's value, i is the number of the value measured, A_i is the alternative's score on the i^{th} value measure, $v_i(A)$ is single dimensional value of score of A_i , and w_i is the weight of i^{th} value measure. ($\sum_{i=1}^n w_i = 1$) (Parnell, Driscoll, and Henderson, 2008).

Value functions measure returns to scale on the value measures. There are four basic shapes: linear, concave, convex, and an S-curve. In the linear value function, each increment of the measure is equally valuable and adds same value to overall measure. In the concave value function, each increment of the measurement is worth less than the preceding increment and adds less value to overall measure. In the convex value function, each increment of the measure is worth more than the preceding increment and adds more value to overall measure. And finally, the S-curve has the characteristic of both convex and concave since it involves both value functions (Parnell, Driscoll, and Henderson, 2008). For the model proposed in this study, a simple linear value function will be used for each of the attributes.

After defining the ranges for each objective/attribute, and measuring the value, the next step is to find the additive value of individual objective/attribute to the overall effectiveness. Every individual measure of effectiveness has value associated with it. This allows decision makers to convert disparate measures (km, tons, lbs, %availability etc) into a common unit, effectiveness. It also sets bounds on needed performances. Figure 58 shows an example of how to compute the value function using the linearity. As mentioned before, it is assumed that all value functions are linear. The value function is given by

$$v_i(A) = \frac{\text{measured value} - \text{not enough}}{\text{good enough} - \text{not enough}} \quad (22)$$

where measured value is the measurement of specific objective/attribute, not enough is the down limit of the range of individual objective/attribute, and good enough is the upper limit of the range of individual objective/attribute. “not enough” and “good enough” values are defined by decision-makers. By doing this calculation, a linear scale is established between minimum value (0) and maximum value (1).

After calculating each individual attribute’s value function, the last step in calculating the overall measure of effectiveness is to apply equation (21). For any

level of objectives/attributes in the hierarchical structure, the total measure of effectiveness is expressed by the sum of products of each attribute's additive value and the assigned weight of that attribute.

Weights play a key role in the measure of effectiveness model. The weights can be considered as the mirror of the decision-maker since the decision-maker's preferences will form the priorities in the attributes or objectives. Weights assigned to each individual objective/attribute and the defined range to set the best and the worst value for individual objective/attributes directly affect the result of measure of effectiveness. That is why the decision-makers must be careful and sensitive while forming the measure of effectiveness structure, deciding on the assigned weights and defining the ranges. There are many subjective ways to determine the weights, but there are some other ways that the weights are assigned more precisely, in which the preferences of the group are represented in a better way. One common way to assess weights from a group of experts is defined in the open literature as:

- *Vote. (Have each individual spread 100 points over the value measures based on the measures' range.)*
- *Discuss significant differences. Have the "outliers" discuss their rationales.*
- *Revote until the group agrees on the ordinal ranking of the value measures.*
- *Vote again requiring each person's weights to follow the group's ordinal ranking of the value measures.*
- *Average the weights (cardinal ranking of weights) and normalize so they sum to one.*
- *Discuss significant differences. Have the "outliers" discuss their rationales.*
- *Repeat last two steps until the group agrees (Parnell, Driscoll, and Henderson, 2008).*

According to this approach, if there are disagreements about the weights that can not be resolved, they must be recorded for later evaluation of alternatives in order to do a sensitivity analysis to determine if they are significant. Mostly, the preferred alternatives are not sensitive to the weight range evaluated (Parnell, Driscoll, and Henderson, 2008).

For this study, a common-sense approach will be used to assign the weight for each attributes and the objectives.

B. MEASURE OF EFFECTIVENESS MODEL FOR ELECTROMAGNETIC WEAPONS

Measure of effectiveness model for electromagnetic weapons is slightly different from any model for lethal weapons. The most important features of electromagnetic weapons are that they are not lethal, not explosive, but capable of degrading the opponent's electronic systems. Since there is no published/proven electromagnetic weapon on the shelf, the proposed model will assess mostly the qualitative aspect of electromagnetic weapons. Since the purpose of this study is to show whether the e-bomb is worthy of R&D facilities, the proposed model is intended to be useful to make a recommendation for this question.

The effectiveness of electromagnetic weapons are evaluated under five objectives: Design, Compatibility, Lethality, Operational Suitability and Human Factors. Each of them are identified, including the sub-objectives/attributes. Then, they are weighted according to the importance given by the author of the study. Next, the acceptable range for each individual attribute will be defined, and finally, assigned value if each attribute is computed to show the overall effectiveness on electromagnetic weapons. Figure 55 shows the proposed measure of effectiveness model structure.

Various colors show the separation between the levels in the hierarchy. According to the color designation, pink represents second level, yellow represents third level and blue represents fourth level of objectives/attributes.

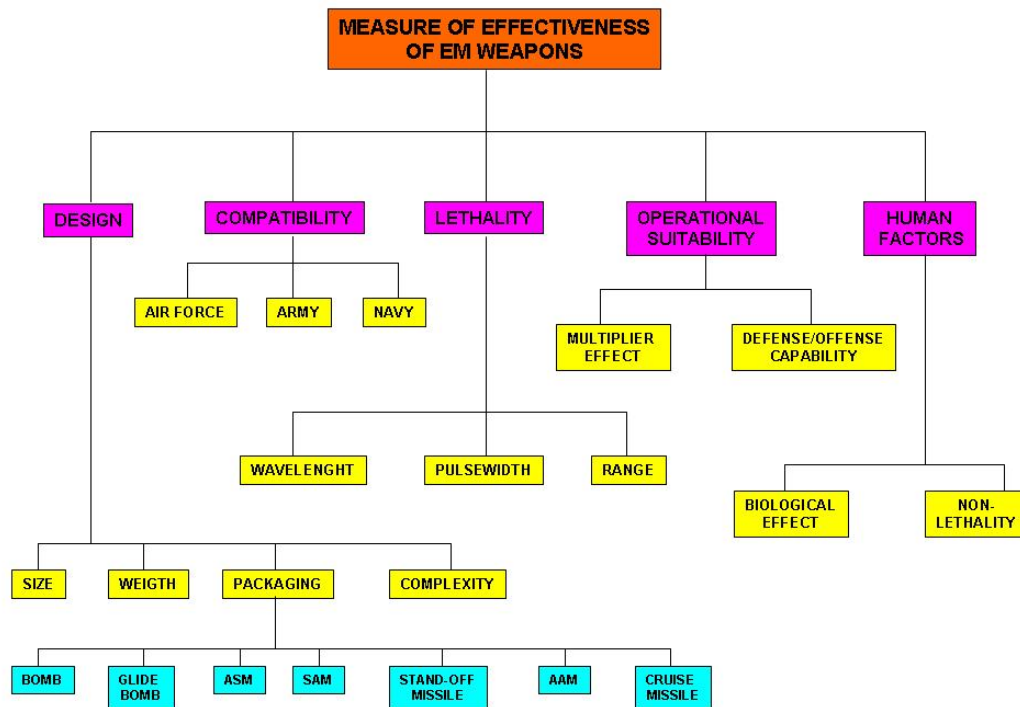


Figure 55. Measure of Effectiveness Model for Electromagnetic Weapons

The weights assigned to each individual second level objective are:

- DESIGN : 0.10
- COMPATIBILITY : 0.15
- LETHALITY : 0.50
- OPERATIONAL SUITABILITY : 0.20
- HUMAN FACTORS : 0.05

The most important measurement for comparing the weapons is of course the lethality. Even though electromagnetic weapons are non-lethal weapons against human, there is still a lethality issue against electronic systems. For this objective, it is intended to give more effectiveness to the weapon with more effect on electronic systems. More lethality means a better electromagnetic weapon. The attributes that drive lethality are the lethal range of the weapon, wavelength

and pulsewidth of the signal. Lethality range is a measurable factor. The expected potential lethality will be used as the lethality range of the notional e-bomb.

For the comparison, the lethality range will be determined against a specified target. For this study, Swedish fighter aircraft will be that target. The second attribute, wavelength, determines the coupling efficiency of the electromagnetic weapon. Shorter wavelengths generally offer better coupling performance, better power transfer performance, and better antenna performance for a given antenna size (Kopp, 1996). The last attribute, pulsewidth, is an important determinant of damage threshold power. The damage threshold power required for thermal second breakdown is given by

$$P_D = A_J \frac{K}{\sqrt{\tau}} \quad (24)$$

where A_J is the junction area of representative electronic device, K is the proportionality constant and τ is the pulsewidth of the signal (Taylor and Giri, 1994). According to equation (24), the higher pulsewidth results in lower damage threshold power. That is, less power is enough to create a damage effect on target. For the measure of effectiveness model, the greater pulsewidth is better in order to provide damage on intended target. The “weights,” “good enough” and “not enough” values are provided in Table 19 for lethality range, pulsewidth and wavelength.

Attributes	Weights	Good Enough	Not Enough
Lethality Range	0.70	200 km	1 km
Wavelength	0.15	0.05 m	2.0 m
Pulsewidth	0.15	1000 ns	10 ns

Table 19. MOE values for lethality attributes

The second most important objective is operational suitability. By Operational suitability measures the role of the weapon in the battlefield. Some weapons are used to defend the units/systems where others are used to attack/destroy enemy units/forces. Similarly, some weapons are effective only on one target where others are mass-destructive. For the comparison of electromagnetic weapons in terms of the operational suitability, two attributes are proposed to drive the effectiveness: Multiplier effect and Defense/Offense Capability. Multiplier effect is the ability of electromagnetic weapon to achieve kills against multiple targets of diverse types within its lethal footprint. This is defined as qualitative measurement in the model. Assessment is made whether the weapon is capable of achieving this particular mission or not. The second attribute, Defense/Offense Capability, is the definition of electromagnetic weapon in terms of tactical usage. For the comparison, an offensive weapon is assumed better than a defensive weapon. The “weights,” “good enough” and “not enough” values are provided in Table 20 for operational suitability attributes.

Attributes	Weights	Good Enough	Not Enough
Multiplier Effect	0.70	YES=1	NO=0.5
Defense/Offense Capability	0.30	Offensive=1	Defensive=0

Table 20. MOE values for operational suitability attributes

The third objective is the compatibility, the integration of the electromagnetic weapon with different platforms (degree of usability with navy, army or air forces). This attribute is measured qualitatively. One weapon can be compatible with surface ships, but not aircrafts. If it is compatible with any platform, it adds value to the compatibility measure. Compatibility with air forces is considered to be the most important since most electromagnetic weapons are meant to be used as SEAD (suppression of enemy air defense) operation. It is

assumed that in the future, mostly air forces will use the electromagnetic weapons. The “weights,” “good enough” and “not enough” values are provided in Table 21 for compatibility attributes.

Attributes	Weights	Good Enough	Not Enough
Air Forces	0.50	YES=1	NO=0
Navy	0.25	YES=1	NO=0
Army	0.25	YES=1	NO=0

Table 21. MOE values for compatibility attributes

The design (physical and technical characteristics) of an electromagnetic weapon either for bomb or missile application, is an important issue. The size, weight, complexity and packaging are main factors that drive the design of electromagnetic weapon. The size of the weapon can limit the power source, in turn constraining the lethality and means of delivery. If the size is small, the required power to damage the target can not be packed into the weapon. Similarly, if the size is large, in this case it will limit the flexible use of weapon. That is, the weapon can be used to defend any unit, but can not be delivered as a missile. For the proposed model, qualitative measures will be used to define the size of the weapons. Small and large size is not good, where moderate size is more desirable for electromagnetic weapons. Weight can also be a limiting factor for the means of delivery. If it is a heavy weapon, it can not be delivered as missile or glide bombs. In this case, a lighter weapon is more desirable. Weight is also a qualitative measurement. Another attribute, packaging, is the ability of electromagnetic weapon to be packed in different warheads such as bombs, glide bombs, missiles etc. This flexibility can provide tactical advantage for the electromagnetic weapon. If any weapon can be carried within a cruise missile, or stand-off missile, the operational effectiveness of the weapon will clearly increase. The packaging attributes are measured whether the weapon has that

individual flexibility or not. The last attribute under the design is the complexity. Since the technology is not mature in this area, a qualitative value is assigned to each electromagnetic weapon according to the technological complexity for design. The “weights,” “good enough” and “not enough” values are provided in Table 22 for design attributes.

Attributes	Weights	Good Enough	Not Enough
Size	0.25	Moderate=1	Small,Large=0
Weight	0.25	Light=1	Heavy=0
Packaging	0.25		
Bomb	0.14	YES=1	NO=0
Glide Bomb	0.14	YES=1	NO=0
ASM	0.14	YES=1	NO=0
SAM	0.14	YES=1	NO=0
Stand-off Missile	0.16	YES=1	NO=0
AAM	0.14	YES=1	NO=0
Cruise Missile	0.14	YES=1	NO=0
Complexity	0.25	LOW	HIGH

Table 22. MOE values for design attributes

The last objective is human factors. There are two attributes defined as drivers for human factors: non-lethality and environmental effect. Even though all electromagnetic weapons are meant to be non-lethal weapons, non-lethality is considered to be an important attribute, which is shown in the proposed model. If the weapon is not lethal, it is assumed that it is better for humanity. The other attribute is the environmental effect of the electromagnetic weapon. It is generally accepted that biological effects from radiation occur as a result of power

absorption. For animals and humans, this process is complicated by non-uniform power absorption and the internal thermal regulation process. Clayborne and Giri define biological effects due to the radiation (Taylor and Giri, 1994). According to the data, exposure levels less than 100 W/m^2 does not have any biological effect. For human factors, the less biologically effective weapon is the better electromagnetic weapon. The exposure level will be converted to the range in meters. Corresponding range represents the maximum range that an electromagnetic weapon can have biologic effects on humans. Figure 56 shows the maximum biological range of high-tech e-bomb. Beyond 522 meters, one can say the e-bomb is not dangerous to humans.

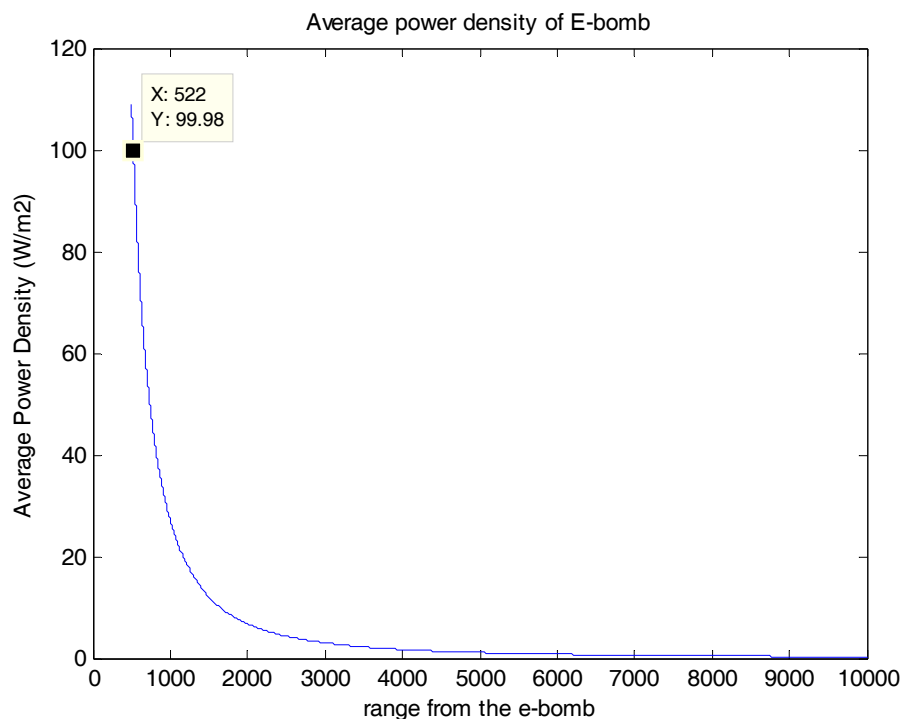


Figure 56. Maximum biological effect range of e-bomb

The “weights,” “good enough” and “not enough” values are provided in Table 23 for human factors attributes.

Attributes	Weights	Good Enough	Not Enough
Non-lethality	0.50	YES=1	NO=0
Biological Effect	0.50	500 m	10,000 m

Table 23. MOE values for human factors attributes

At the very least, the method of analysis for measure of effectiveness proposed in this study offers a way to choose the numerical quantities related to the electromagnetic weapons that are consistent with each other, with an assumed objective, and with the decision-maker's expectation of the future. The methods provides its answers by process that are accessible to critical examination, capable of duplication by others, and more or less, readily modified as new information becomes available.

Figure 57 shows the MOE of EM weapons with weights.

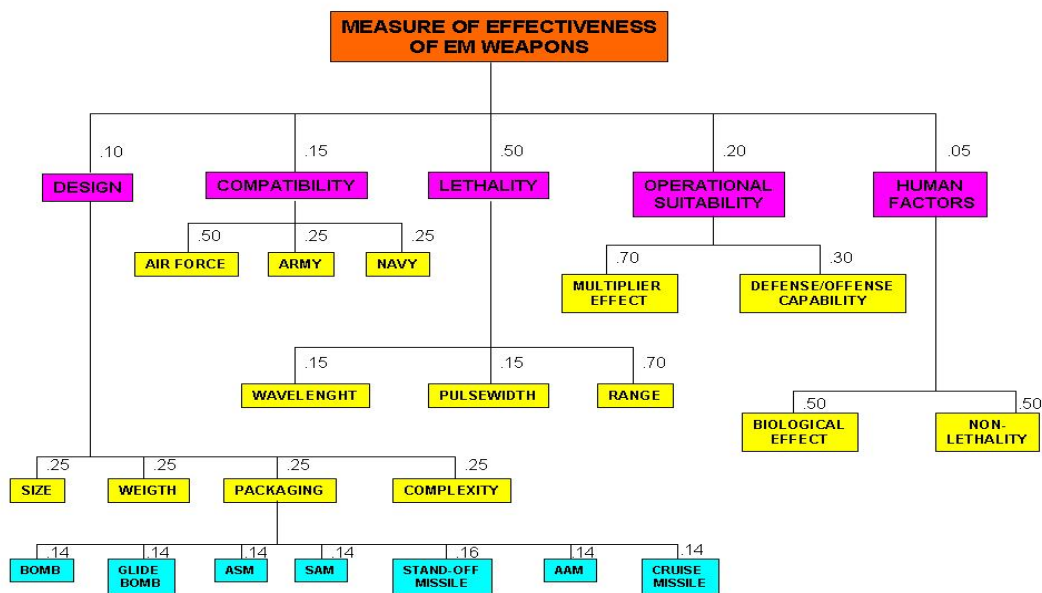


Figure 57. Measure of Effectiveness Model for Electromagnetic Weapons with weights

C. ANALYSIS OF THE MODEL OUTPUT

The specification of each electromagnetic weapon in terms of the measure of effectiveness attributes is defined in Table 24. For the hypothetical e-bomb, high-tech (powerful) e-bomb will be used as reference.

Specifications	HEMP	HPM Weapon	E-Bomb
Design			
Size	Moderate	Large	Moderate
Weight	Light	Heavy	Light
Packaging			
Bomb	NO	NO	YES
Glide Bomb	YES	NO	YES
ASM	NO	NO	YES
SAM	YES	NO	YES
Stand-off Missile	NO	NO	YES
AAM	YES	NO	YES
Cruise Missile	YES	NO	YES
Complexity	HIGH	MODERATE	MODERATE
Compatibility			
Air Forces	YES	YES	YES
Army	YES	YES	YES
Navy	NO	YES	YES
Lethality			
Range	450 km*	~10 km	160 km**
Pulsewidth	500 ns	1000 ns	100 ns
Wavelength	1.5 m	0.1 m	0.15 m
Operational Suitability			
Multiplier Effect	YES	YES	YES
Defense/Offense Capability	Offense	Defense	Offense
Human Factors			
Non-lethality	YES	YES	YES
Biological Effect***	27,272 m	538 m	522 m

Table 24. MOE Specification of Electromagnetic Weapons

* As mentioned before, the electric field measured in Honolulu (800 miles away from the Starfish test facility) was 5.4 kV/m. Such an electric field will have field strength of 15 kV/m (the threshold level for Swedish Fighter) at 450 km.

** Even though the lethality range of proposed e-bomb against Swedish Fighter Aircraft is about 10 km, since the e-bomb can be delivered as cruise

missile, or any other missile, the average reasonable range of the missile (150 km) is added the lethality range of e-bomb.

*** Biological effect ranges are calculated by estimating the range at which the power density becomes 100 W/m^2 .

For the specifications of the HEMP, the open literature data has been used. For HPM weapon specifications, the proposed weapon ($f=3 \text{ GHz}$, antenna aperture = 100 m^2 , pulsewidth=1000 ns) by Clayborne and Giri has been used.

Using the data given in Table 24, each electromagnetic weapon is assessed in terms of the effectiveness model proposed by this study.

Figure 58 shows the measure of effectiveness organization with weights and attribute values.

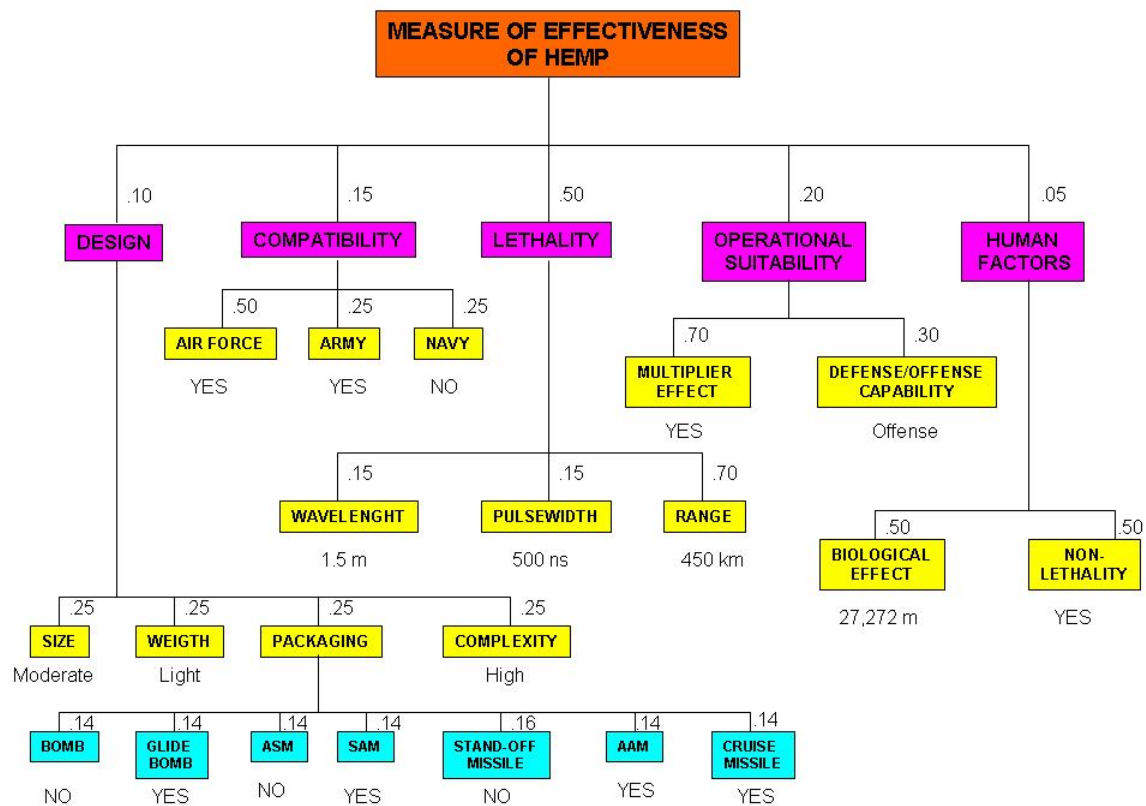


Figure 58. MOE of HEMP

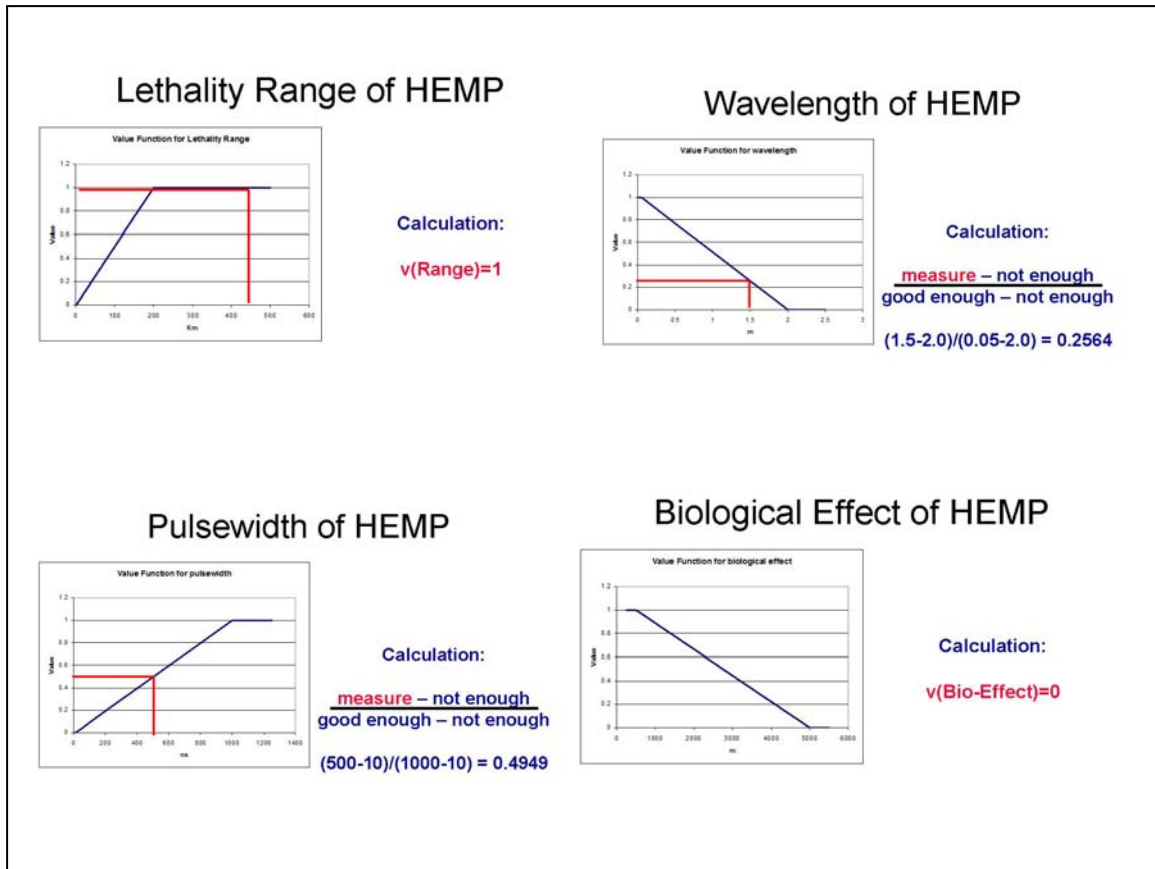


Figure 59. Single attribute calculations for HEMP

After finding the single individual attributes (Figure 59), the additive value method gives the overall effectiveness of HEMP under the assumed model, as to be 0.8078.

The same methodology is applied to measure the effectiveness of HPM weapon. Figure 60 shows the MOE structure for HPM weapon including assigned weights and the measurements/assumptions of each attributes.

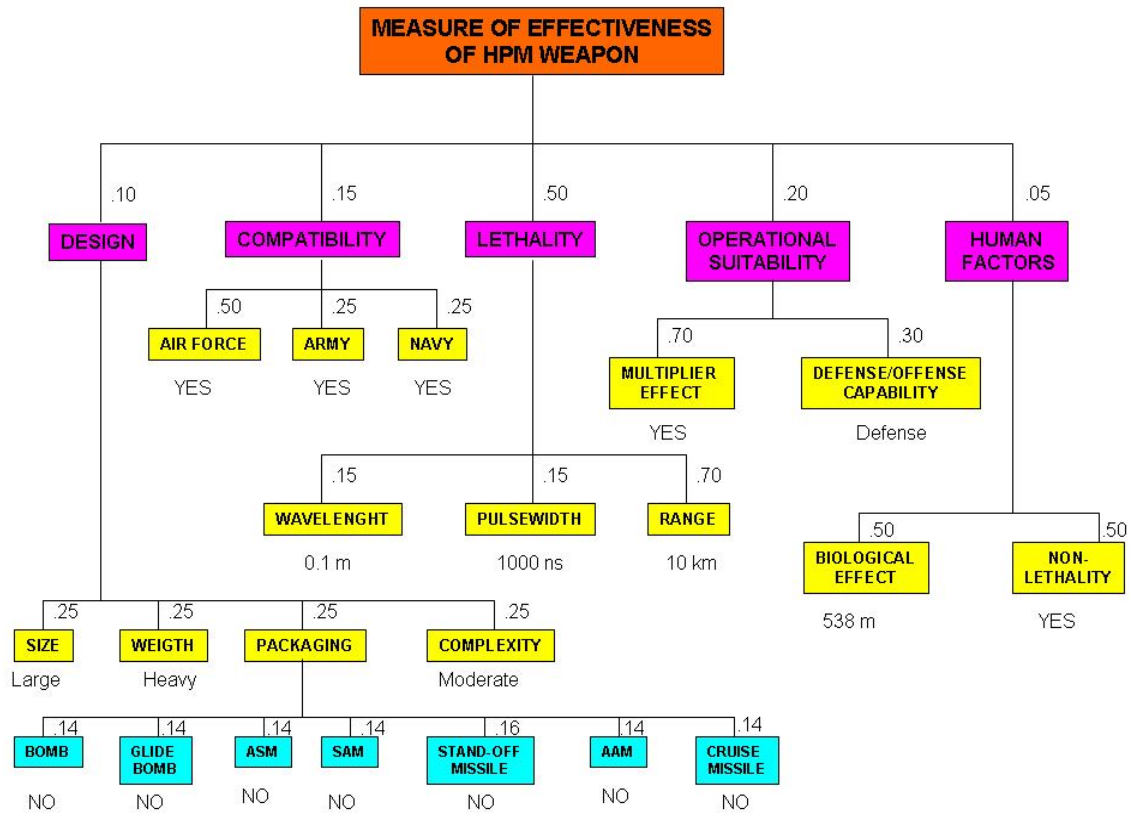


Figure 60. MOE of HPM Weapon

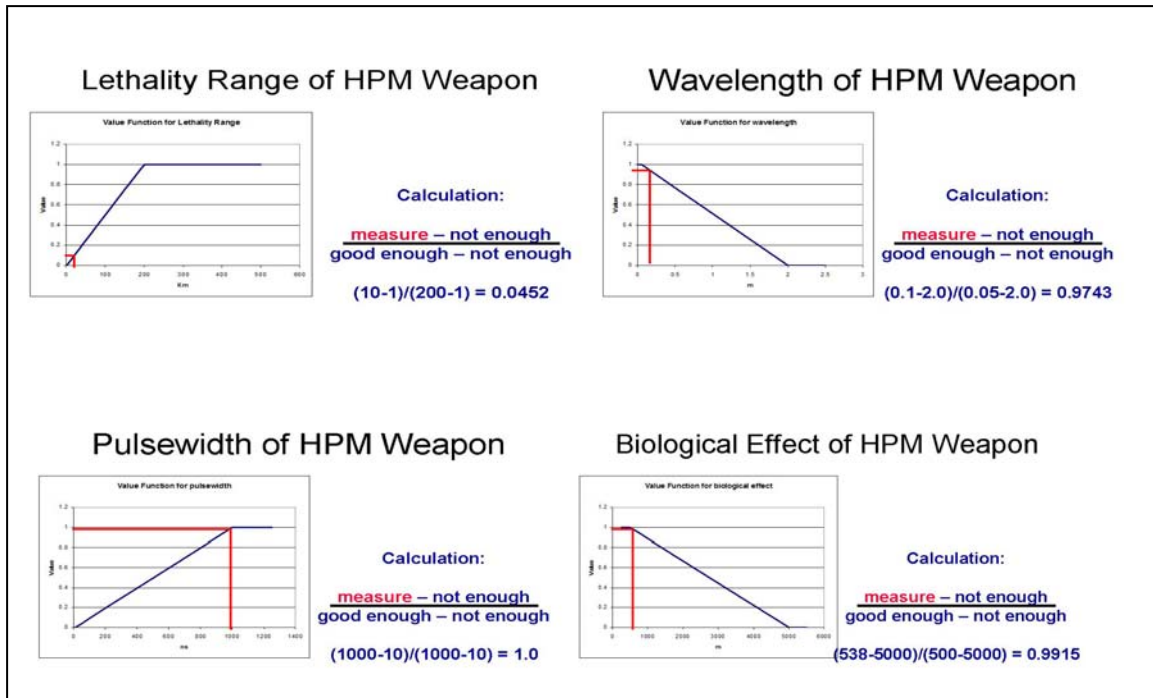


Figure 61. Single attribute calculations for HPM weapon

When same single attribute calculation is done (see Figure 61) and the additive value method is applied, the overall effectiveness of HPM weapon is found to be 0.5162. And finally, the same method is followed for the measurement of effectiveness for e-bomb. Measured/assumed values for an e-bomb are shown in Figure 62.

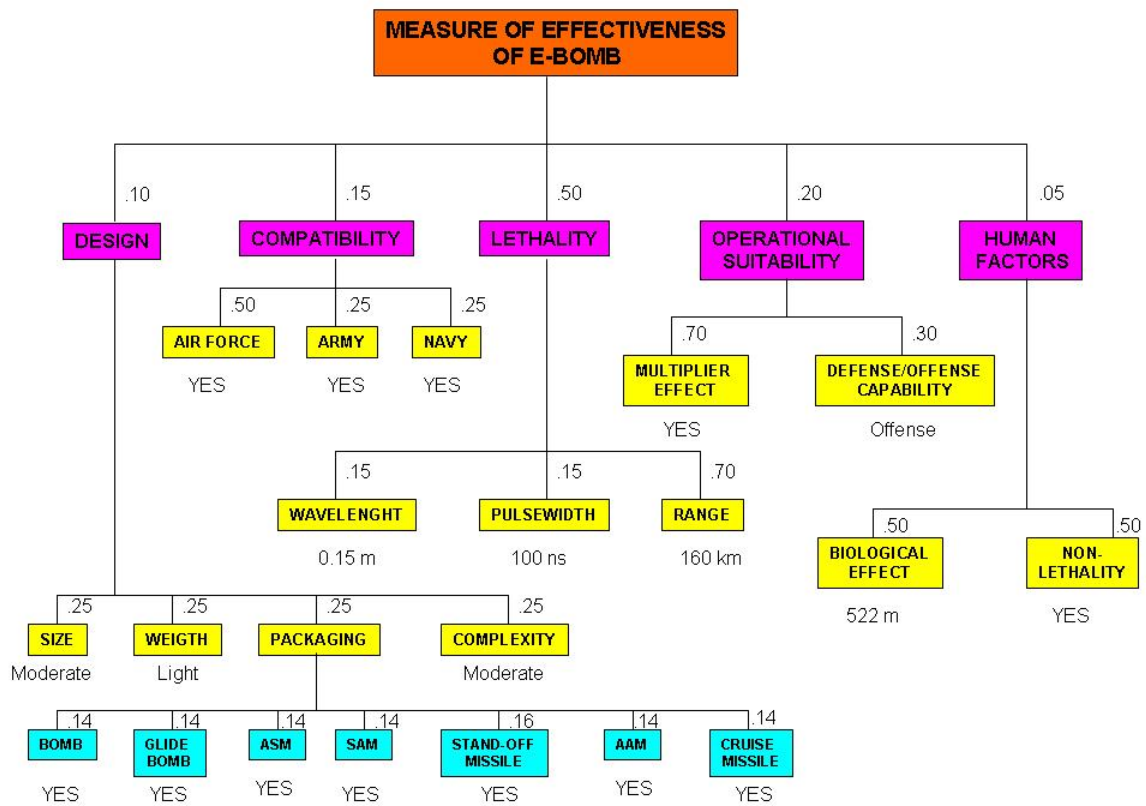


Figure 62. MOE of E-Bomb

The single attribute calculation (see Figure 63) and the additive value method show that under the assumed model, the overall effectiveness of e-bomb is 0.8449.

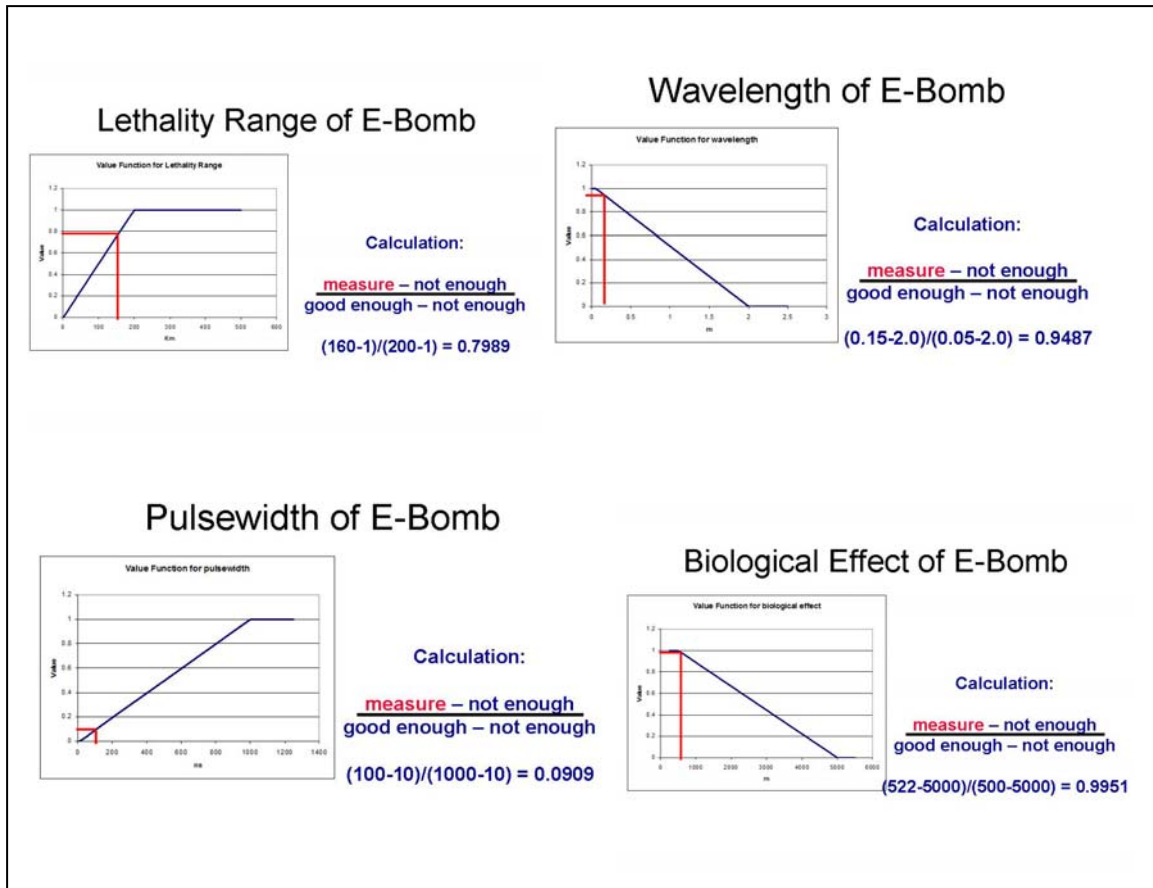


Figure 63. Single attribute calculations for E-Bomb

Since, technologically similar methods are applied to produce such weapons, and there is no reported electromagnetic weapon that has a credible cost estimate, the costs for all electromagnetic weapons proposed in this study are assumed to have same magnitude of cost. This turns the problem into a “maximizing the effectiveness” problem. When three effectiveness models are compared, one can realize that the proposed e-bomb has the best effectiveness among all other options. Surely, the analysis has so many deficiencies. However, if it is considered that there is no real weapon in this area, the purpose of this study can be understood better. This study tries to show that in the future, such weapons will have an important role in the battlefield. Among these weapons, the e-bomb deserves to get the most attention for exploring.

Another interpretation could be that the e-bomb is a mass-destructive non-nuclear electromagnetic weapon. When considering that the HEMP is known as the electromagnetic effect of the nuclear bomb, the cost-effectiveness analysis shows that the e-bomb has also same effect with HEMP.

The HPM weapons are large in size and weight and have a short range. These features make it a fixed weapon. That is why the effectiveness of the HPM weapon is relatively less than the other two electromagnetic weapons. In fact, with its huge design, it is not useful in the battlefield for offensive purposes. It can, however, be used as a defensive weapon against missiles.

On the other hand, HPM weapons are important because they provide the theory for proposed hypothetical e-bombs. With different applications, such as missile, cruise missile etc. the e-bomb can be used as effectively as HEMP.

The proposed model to measure the effectiveness of electromagnetic weapons is believed to be organized to give the best effectiveness analysis. However, it is open to interpretation. Nevertheless, since the qualitative data in this study is limited, and the qualitative data provided is calculated based on the published theoretical data rather than physical measurement, the output of the model may be accordingly inaccurate. If the real data for the proposed model can be measured in the future, the output of the model will be at least somewhat different from the output of this study.

If satisfactory solutions can be found for future problems in e-bomb design, e-bombs promise to be an important and robust weapon in both strategic and tactical operations, offering significantly reduced collateral damage and lower human casualties than established weapons.

V. E-BOMB IN MILITARY RIVALRY

In a future war where all sides depend heavily on electronic systems, weaponry and command and control, a weapon that disrupts and damages these systems will be extremely valuable. If it can perform this function at the speed of light, with minimal prior target information and with minimum collateral damage, it will be especially useful (Bolkcom and Tatman 1997).

The rules of battle have changed over the entirety of military history. Tools such as technology, strategy, tactics and weapons have been the principal elements determining what kind of rules apply to the battlefield. Accordingly, the rules of the future battlefield are indicated now. Foreseeing future battlefields, and projecting the technologies on which future systems will be based, plays a major role in maintaining a lead position in the military affairs. The country, and its armed forces, must predict the future appropriately and prepare for better than its rivals.

Can our hypothetical e-bomb be a significant weapon for the future battlefield? Can the country that first develops this new weapon have a significant and exploitable military advantage against other powers?

This chapter attempts to answer these questions by discussing the future battlefield and offering a prediction about its principal rules and elements. Military competition in the world, and the elements that bear on the rivalry, can then be explained. Also, this study attempts to clarify the potential role of e-bombs. Finally, the overall implications of the hypothetical e-bomb are analyzed.

A. THE BATTLEFIELD OF THE FUTURE

Military success against other countries depends on actions taken to prepare for the future. The military advantage obtainable with e-bombs is related mostly to their operational significance.

The framework of the battlefield of the future, as defined by the Joint Chiefs of Staff, and the status of Military Technical Revolutions are published in open literature:

In order to plan for the battlefield of the future, the chairman of the Joint Chiefs of Staff released a report called Joint Vision 2010. This report offers a broad framework for understanding joint warfare in the future. It also directs US armed forces acquisition programs in obtaining capabilities to run military operations using precision engagement, dominant maneuvers, and focused logistics while providing full dimensional protection of forces and assets in combat. JV2010 is a reflection of the basic belief that a revolution in military affairs is occurring, and it assumes that new capabilities are needed to cope with that Military Technical Revolution (MTR).

There have been perhaps a dozen revolutions in military affairs since the fourteenth century. One began when the United States detonated its first atomic bomb in the early 1945 Trinity test. The Hiroshima and Nagasaki detonations in August 1945 helped end World War II. In that same war, the Japanese experimented with germ warfare by spreading bubonic plague agents on Chinese population centers via bombing missions. Also in WWII, the Germans manufactured—but did not use—Sarin and Tabun nerve gases. These nuclear, biological, and chemical armaments now form a new "trinity" of weapons of mass destruction that threaten to make twenty-first-century warfare more costly than anything seen before (Schneider and Grinter, 1998).

In the United States, the principles of war are described by the acronym MOSSCOMES (Schneider and Grinter, 1998):

- M - Mass
- O - Offensive
- S - Surprise
- S - Security
- C - Command Unity
- O - Objective
- M - Maneuver
- E - Economy of Force
- S – Simplicity

No matter the era, these principles will be the basis of the war. One of these principles, mass, is most likely to drive the battlefield of the future. A new era in warfare may well be marked by the proliferation of weapons of mass effect. These confer the advantages to be gained by simultaneity and depth of attack, information dominance, and accurate targeting which is defined in different terms in JV2010. For example, with the revolution in accuracy, hundreds of aircraft do not need to drop thousands of bombs to destroy a single target. Instead, one aircraft can deliver a precision weapons to destroy targets and obtain the same results formerly requiring hundreds of sorties.

Research and development work is currently underway on “information warfare” in hopes of transforming the way wars are fought. In short, it is a method for revolutionizing the battlefield of the future using information technology (Giri, 2004). Noting that the microprocessors have doubled in speed every 18 months (Patterson, 1995), it is reasonable to conclude that information warfare will do much to shape the future battlefield.

Fast information flow is getting more and more important every day. Giant organizations such as government, the military, and industry cannot function without fast information flow. The common point of the systems used in these sectors is that they are all built with modern, high-density semiconductor components. Dependency upon these semiconductor components results in more and more vulnerable systems due to the rapid advance of technology. That is, data and communication structures will remain a soft electromagnetic target for the near future. That is because nobody wants to pay for hardening these systems (yet). Hence, there is a fundamental and growing electromagnetic infrastructure vulnerability, exploitable by terrorists (and others) in the near future (Benford, Swegle and Schamiloglu, 2007).

The emergence of information warfare would definitely add new methods of destroying opponent’s targets and disrupting the operations. In this new way of warfare, independent information warfare operations could be the first phase of

the war, since it includes covert attack with adaptable, time-phased computer viruses. Following the first phase, overt attacks using anti-satellite and media override operations, conventional electromagnetic pulse weapons for area effects, and HPM weapon attacks would disable specific targets. In addition to offensive measures, such as temporarily or permanently disabling an opponent's sensor and information-processing systems, integrated information warfare operations could also mislead an opposing force as to the size, location, and orientation of friendly forces (Pfaltzgraff and Shultz, 1997).

One of the defined electromagnetic weapons, HEMP, and the resultant electromagnetic pulse, is believed to render most allied space assets inert. Electromagnetic pulse radiating from such a weapon could burn out the circuitry of most allied radio systems, computers, transistors, and power grids in the region of combat — rendering many of the allies' high-tech assets harmless (Schneider and Grinter, 1998). This gives an important role to such weapons in the information warfare of the future battlefield.

Another report defines the possible information warfare threats to the U.S. in 2010 (Miller, 2005). According to this report, Network Centric Warfare (NCW) will play an important role and start a new era in the battlefield of the future. The operational advantages conferred by NCW depend on networking sensors, increasing speed of command, accelerating the tempo of operations, and achieving greater lethality, through data links, displays, computerized planning systems, GPS receivers, radios, satellite communications, smart munitions, aircraft, and so on. The power of NCW is directly related to the performance of microchip-enabled systems, which are used in nearly every element of NCW. And, of course, as a response to this emerging warfare, new threats will show up. The electromagnetic circuit vulnerability seems the weakest aspect of NCW. Accordingly, weapons that will exploit the vulnerability of NCW will become a major threat.

The environmental effect of conventional weapons is another consideration for future battlefields. It is obvious that the effects of future

conventional weapons will be more than existing conventional weapons. One can say that this will put increased pressure on military planning and lead us to explore new ways of warfare. There are no longer sharp lines in the new battlefield to identify the situation as clear-cut as there once were. In this new way of war, more ambiguity and difficulty on deciding the “good” and “bad” guys make the situations more difficult to identify. The shared interest in the battlefield has been changed. In this new era, the military operations mostly focus on transnational threats rather than survival or protecting the freedom of the citizens. This removes the sharp boundaries of the war and makes them less clear. As a result, the risks to civilian life and infrastructure get higher. Moreover, military forces are often deployed to situations that require close proximity to non-combatant civilians. In addition to the changes in types of threats and the corresponding reaction of military force, there is also the issue of controlling weapon lethality levels and collateral damage.

The potential effect of mass destruction weapons has been made clear since World War II when the nuclear weapon was first used. It has changed the look of people to the strategic weapons. Existing strategic weapons with increased lethality are now too deadly for our own good — and the good of the planet. In addition to improving the accuracy and the precision of conventional/non-conventional weapons, a number of new options to utilize the lethality levels of such weapons are being explored. Even though the cost of the weapons itself can seem relatively normal, the cost in terms of large-scale casualties of civilians, the environment, and the infrastructure in a war zone can be tremendous in modern warfare. An analysis of cost and advantages of modern conventional weapons has created new arguments. Such studies show that it is no longer advisable to continue in our current direction. That is why the conventional weapons with incredible lethality concept may soon be superseded, even though they seem as the only foundation for defense. The new battlefield of the future in the twenty-first century makes new strategies and techniques for combat already available. These new strategies and weapons are designed to

minimize casualties on all sides by being nonlethal in nature. Such weapons are called as “nonlethal weapons” and represent an entirely new classes of nonlethal weapons in the warfare that could minimize the lethality. The main purpose of such weapons, at least in theory, is to degrade the enemy’s capabilities by damaging the systems while causing minimal loss of life. The traditional warfare with conventional weapons is still a major impact in the battlefield, and nonlethal measures are not being proposed as a replacement for conventional weapons. However, there is trend for nonlethal technologies to consider them as a strategic alternative (or supplement) to bloodshed — an intermediate option that allows for a reduction of indiscriminate death and destruction (Giri, 2004).

The Air Force Scientific Advisory Board’s recently published a report about directed energy and HPM technology, which is one of directed energy applications. The following statement by the board explains the future battlefield and the importance of nonlethal weapons:

Promising present-day research in high power microwave (HPM) technology allows us to envision a whole new range of compact weapons that will be highly effective in the sophisticated, electronic battlefield environment of the future. There are many advantages of these HPM weapons: First, there are virtually no target acquisition, pointing, and tracking requirements in any HPM weapon employment scenario. Electromagnetic radiation, traveling at the speed of light, will envelop a large volume that can engage multiple targets at once. HPM weapons could be used in nearly all large volume that can engage multiple targets at once. HPM weapons could be used in nearly all weather, although frequencies above 10 GHz degrade somewhat. HPM weapons designs could be employed in a covert way since the beam is not visible and the damage and/or upset could be directed to electronic targets. Since in many applications the only expendable is fuel for electrical generators, HPM weapons are expected to come with a large “magazine.” It may be possible to design a system that acts as both radar and weapon, which first detects and tracks the target and then increases the power and engages the target, all at electronic speeds. Finally, a distinct advantage of HPM lies in the fact that it may be considered a nonlethal weapon that would prevent the enemy from using his electronic equipment successfully with no impact on human life (AFSAB, 1995).

According to the published reports, one can say that overall dependency of military operations on electronic systems will keep increasing. However, this will increase vulnerability to electromagnetic weapons. The “mass” principle of the war will still be an important element in the future. Therefore, the exploration of electromagnetic weapons in designing as a mass destructive weapons against electronic system may be a new manifestation of the “mass” principle. Thus, information warfare will play an important role in battlefield success.

Also, success in Network Centric Warfare will be a decisive factor in victory on the battlefield. Improving electronic technology will make information warfare and NCW more effective in speed, accuracy, detecting, targeting, lethality etc. However, NCW is more vulnerable against electromagnetic weapons. And, the smaller size and the simplicity of such weapons will make these weapons more useful, and available, as countermeasures to NCW. Accordingly, both terrorists and traditional military organizations can be expected to explore the potential of e-bombs.

B. MILITARY RIVALRY AT PRESENT AND IN NEAR FUTURE

The military technical revolution for the close future of battlefield has been identified in open literature:

Over the next two decades, an emerging military technical revolution (MTR) could have profound consequences for global strategic balances. Driven by a broader information revolution, the emerging MTR could transform war on land, in the air, and at sea, and bring war into two new dimensions – space and the information spectrum. Although the nuclear revolution can be expected to have a continuing, truncating effect on the strategic scope of the emerging MTR, the advent of a post-MTR military regime would complicate planning and result in increased stratification of military capabilities. The United States will almost assuredly enter this period of transformational change well in advance of other competitors, but others inevitably will follow. Asymmetries in strategic requirements, moreover, should cause some competitors to emphasize significantly different aspects of the post-MTR regime (Pfaltzgraff and Shultz, 1997).

Military revolutions have always been the major discontinuity in military rivalry. Such discontinuity occurs by changes in relevant technologies, concepts of operations, methods of organization, and/or resources available. Relatively abruptly, they alter the conduct of war in a different way and enable order of magnitude gains in military effectiveness for the side that made the military technical revolution. Overall, they create a big difference between military regimes in terms of the military advantage (Pfaltzgraff and Shultz, 1997).

A number of definitions for “military-technical revolution” have been introduced in open literature, including:

Geoffrey Parker, discussing the “military-revolution” of 1500-1800 noted major changes in European warfare – battlefield technology, tactics, size of armies, new strategies for larger armies, plus wide-ranging political and societal changes. A study from Georgetown University’s Center for Strategic and International Studies offers “a fundamental advance in technology, doctrine or organization that renders existing methods of conducting warfare obsolete.” One US Department of Defense (DoD) view is that MTRs occur when emerging technologies are applied to military systems, whose use are optimized via custom-tailored operational concepts and force structures, resulting in vast increases in military effectiveness. No matter what definition is used, it is clear that MTRs have an important impact on military capability to those able to exploit them. Military Technical Revolutions (MTR) are inherently part of military competitions (Franck and Hildebrandt, 1996).

According to Andrew Marshall, director of the Office of Net Assessments in the Office of the Secretary of Defense,

Military Technical Revolution is a major change in the nature of warfare brought about by the innovative application of new technologies which, combined with dramatic changes in military doctrine and operational and organizational concepts, fundamentally alters the character and conduct of military operations.

One can say that such an MTR is now happening and those who understand and applies will definitely take advantage of it and enjoy a decisive advantage on the battlefield of the future (Schneider and Grinter, 1998).

In future warfare, the struggle for information, in other words “information warfare,” will play a central role, taking the place, perhaps, of the struggle for geographical position held in previous conflicts. Information superiority is emerging as a newly recognized, and more intense, area of possible future competition. In response to these developments, command and control systems must be designed to provide commanders at all levels the accurate information and uninterrupted communications needed to direct the dispersion or concentration of their forces and, more importantly, weapons’ effects at the decisive point in time and space. One can consider to develop the command and control system first and then to choose an appropriate weapon according to the design of command and control system structure. This is in interest because any new weapon that is the most lethal weapon among all others does not have chance to be a master weapon in the battlefield unless it is integrated with the command and control system. Moreover, many of the major parts of future weapon systems such as Global Positioning System (GPS), worldwide communications, surveillance and reconnaissance platforms, etc., are already on the shelves. The dominating weapon of the future will be the weapon that will be inoperable with these global command and control system. Even though the conventional weapons developed to interoperate with command and control systems can be dominating weapons, it is obvious that any weapon that developed for employment against command and control systems could degrade significantly the power of the opponent by making the dominating weapons useless.

Future battlefields will be won by the countries that best manage the revolution in military affairs. The key aspects of military revolution are defined in three words: Defense, Technology and Management. Figure 64 shows how these aspects are related and where the military-technical revolution is located. The Defense-Technology aspect focuses on the instruments of war no matter what the military revolution is about. Military technology plays an important role for this aspect. Information warfare falls into this category (Matthews and

Treddenick, 2001). Network Centric Warfare also falls into this category. Communication and the coordination are important factors for NCW, as mentioned above. The Defense-Management aspect focuses on the allocation of defense resources. Logistics, acquisition, project management, budgeting etc. fall into this category. The last aspect, Technology-Management, focuses on the increasingly important policy significance attached to the creation and dissemination of technological innovations across the civil-military sector. Numerous facets fall into this category, including the development of appropriate technology policies to promote invention and innovation, the encouragement of higher levels of civil-military integration, and management and control of defense-related technologies etc.

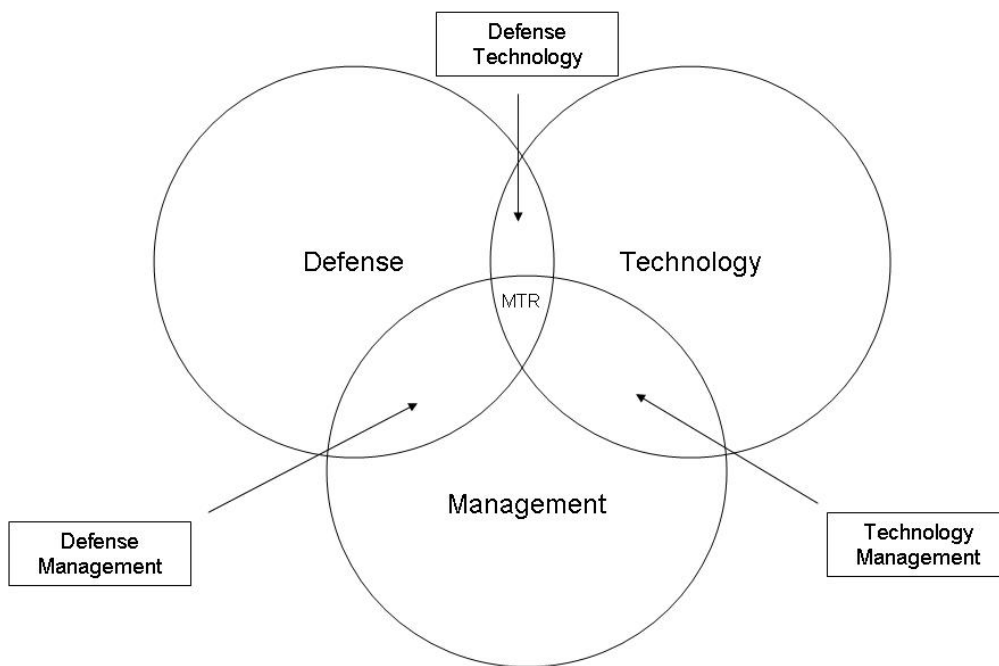


Figure 64. The Military-Technical Revolution: Defense, Management and Technology (Matthews and Treddenick, 2001)

This framework shows that the military revolution of the future does not include just the innovation of new technologies. It is more than that as explained in the structure. However, it can be seen that military revolution involves mostly the technological innovations, new weapon explorations, information management, and encouragement in investment of new developments. It is clear that the side that can manage all these aspects will be successful in the military technical revolution and make differences in military rivalry.

Technology is not a winner on its own, but it has been, and it will continue to be, a critical enabler. If everything else is equal, the side with better technology will win.

When the current military technical revolution is evaluated, one can say that the United States has been in an excellent position to derive military advantages. Such exploitation has four major acknowledged key elements:

- *The technology must be available. It has been in development for at least a quarter century, in both military and civil sectors.*
- *The military must recognize the operational potential of the technology. American authorities, civilian and military, have understood the battlefield potential of the new technology from the beginning stages of development.*
- *The military establishment must officially accept the implications of the new technology, modify its view of warfare accordingly, and take the necessary programmatic steps.*
- *New military organizations must embody the technology, weapons and doctrine fully to exploit the revolution (Franck and Hildebrandt, 1996).*

Cheng Mengxiong, from the Beijing Institute of Systems Engineering, offers an engineer's perspective of key future developments related to the technology that may be key factors in MTR (Matthews and Treddenick, 2001):

- *Weapons, soldiers and combat platforms will be “information intensified” by 2010-2020.*
- *Robot sentries, robot engineers and unmanned smart tanks will be fielded by 2020.*
- *Robot troops will be used in large numbers.*
- *High performance microwave will destroy opponents systems.*

The last bullet implies that electromagnetic weapons will be the main threat for the future battlefield. Anyone who will explore the potential effect of such weapons will be more likely to dominate the information warfare.

Three available basic approaches are defined in open literature in order to respond to opposing military capability: emulations, offsets, and bypasses. *“Emulation involves replication of forces, typically some sort of mirror-imaging, but possibly ways to match rival capability through a different combination of forces. An offsetting response is likely to be a set of countermeasures to negate military effectiveness or disrupt operations. Bypassing responses involve developing new means warfare to leapfrog the rival’s capabilities, or methods of operation designed to avoid them”* (Franck and Hildebrandt, 1996). (Summarized in Table 25.)

Any approach chosen by any country will move that country forward in military technical-revolution. Nevertheless, if one assesses the efficacy of each of these approaches, it is clear that offsetting and bypassing can contribute more than emulating in military rivalry. If the resources and the budget of one country are limited, emulating can be a good approach in order to close the gap with other countries. In addition, technology that has not yet emerged entails higher risks than proven technologies. However, the benefit and advantage that one country can get when it succeeds in developing and exploiting a new technology can be a big step in military rivalry. Overall, there is a tradeoff between risk and possible benefits. Many factors, including available resources, policies, national strategies, geopolitical locations etc., must be considered in deciding which approach should be chosen in order to stay in the military rivalry.

<p>A. Emulating</p> <ol style="list-style-type: none"> 1. Mirror image: nearly identical forces 2. Substitution: equivalent capabilities with different forces, equipment, doctrine, etc.
<p>B. Offsetting</p> <ol style="list-style-type: none"> 1. Defense: negating the effects of opposing capabilities 2. Disruption: dislocation of opposing force operations
<p>C. Bypassing</p> <ol style="list-style-type: none"> 1. Avoidance: methods of warfare that avoid enemy strengths (making them irrelevant if possible) 2. New innovation: funding new and better tools of warfare

Table 25. Classifications of Responses to Military Innovation (Franck and Hildebrandt, 1996)

MTRs and military competitions can be considered as inseparable since any change in one of them will affect the other one. New technology that has application in military systems creates opportunities for military innovations, which in turn lead to responses, counter-responses and all the interactions of military competitions. The nuclear MTR can be a good example for this interaction.

The United States was first to exploit the nuclear MTR by developing a large fleet of bombers capable of global strikes. The Soviet response was mostly offsetting (extensive air defenses) and bypassing (ballistic missiles), but included an emulation component (a small strategic bomber force) as well. In turn, the United States chose to offset air defenses through a combination of tactics, countermeasures, reduced signatures and air-launched missiles – and to emulate ballistic missile deployments. (Franck and Hildebrandt, 1996).

Current U.S. attention to install some defensive systems in some European countries to counter theater ballistic missiles is another example of this interaction in a contemporary setting

Finally, technological advance based on the integration of capabilities that exist with new ones as they arise, can make a major difference in military rivalries. War is still a matter of ideas, emotions and will. The military technology and the weapons are just a tool in military rivalry. The masters of the art are to put those capabilities together in innovative ways to achieve national objectives. Those who can accomplish these can make a difference in the battlefield of the future (Tilford, 1995).

C. THE EFFECT OF E-BOMB IN MILITARY RIVALRY

Some key factors that can drive the future battlefield have been defined. The next military rivalry and the key elements that play a decision-making role in military rivalry have been identified. Within this structure, our hypothetical e-bomb is a potential weapon that could play a key role in military affairs. The following paragraphs will try to explain these aspects.

Early innovators gain advantages that rivals must redress by one means or another (or cease being rivals). In fact, full exploitation of new weapon entails effective combinations with other combat arms in new organizations (Franck and Hildebrandt, 1996). From this perspective, the e-bomb (if developed and deployed) is a new weapon since there is no officially reported e-bomb in the world. Any country that can develop such a weapon will likely be the first to employ it, and may well dominate this area for a significant period of time.

One of the principal elements of the war, "mass," may well be reassessed with the advent of e-bombs. It has been shown in this study that the proposed e-bomb has significant battlefield potential. It can achieve operational effects generally associated with weapons of mass destruction (such as nuclear warheads). Information warfare can be seen as central to the ongoing revolution

in military affairs. Fast information flow and communication are elements crucial to this form of warfare. Since almost all of the systems include high-density semiconductors, the proposed e-bomb is a weapon that effectively attacks the hardware that makes information warfare possible.

It can be said that the current MTR is based on the microchip. This incredibly improving technology is the base for possible rapid transmission and assimilation of operational data. High-resolution sensors, precision guidance capabilities for weapons and delivery platforms, and high-speed command, control and communications are some examples for the military applications associated with the microchip (Franck and Hildebrandt, 1996). The Network Centric Warfare is also another way of fighting in the future. Sensors, speed of command, data links, computerized planning systems, radios, and aircrafts are some of the elements that characterize the NCW. The common feature of these elements is that they all involve microchip technology, which makes them vulnerable to the proposed hypothetical e-bomb. That is, the proposed e-bomb is a potential threat against the Network Centric Warfare. Even though it may not disable the entire network, it may degrade the speed of operational tempo, temporarily or permanently disable some elements in the network, and, as a result, decrease the overall network richness significantly.

One of the principal elements of the war, maneuver, is based on enhancing mobility on both offensive and defensive capabilities (Schneider and Grinter, 1998). Note that the proposed e-bomb is more likely the HPM weapon with a high degree of employment flexibility. The disadvantages of HPM weapons, such as limited potential lethality range, heavy size etc., can be overcome in proposed e-bomb designs.

Almost every era of military history has featured a major/dominant weapon. That is, the country that has this weapon is most likely the dominant military power. This fact will not change in the future. The future battlefield requires conventional weapons to integrate with the command and control systems. Command and control systems do not accomplish anything by

themselves. However, even dominant conventional weapons will probably not be useful without capable command and control systems. That is, if one country can degrade the opponent's command and control systems, the opponent country will not be able to benefit from its conventional weapons superiority. The proposed e-bomb can greatly degrade command and control systems, which, in turn, would degrade the usefulness of conventional weapons.

HEMP is widely believed to render most allied space assets inert. As shown above, our notional e-bomb can appear similar to a HEMP weapon (within the atmosphere). Even though the cost of each individual electromagnetic weapon proposed in this study is assumed to be equal, one can easily say that our notional e-bomb will be less expensive, perhaps small, relative to HEMP. The design and technology for an e-bomb is also expected to be simpler and easier than those in the HEMP.

Even if the effects of nuclear weapons continue to be the most important element in future military rivalries, with HEMP being a nuclear weapon intended for electronic devices, the proposed e-bomb can be as significant as HEMP, and thus be an important factor in military affairs.

As Cheng Mengxiong, from the Beijing Institute of Systems Engineering, mentioned, HPM weapons must be considered a key future development in the military technical revolution since they have potential to destroy the opponent's electronic systems. Because of size and design, HPM weapons are likely to be used primarily for defensive purposes. On the other hand, the proposed e-bomb is identified as an HPM weapon that can be used for offensive purposes. It must be noted that, if HPM weapons are considered a key future development in MTR, the proposed e-bomb can have more impact than HPM weapons.

In this study, three types of e-bomb have been proposed. The purpose is to show that even though one does not have deep engineering capabilities, it is possible to produce an e-bomb by using commercially available devices. Maybe this weapon will not be militarily significant, but it generates more power than the

upset/damage threshold level of unshielded civilian systems. This makes such weapons quite interesting for terrorists. If this continues to be a major threat, the appearance of operational e-bombs will also prepare military powers to improve defensive measures against such weapons — even if the first e-bombs are small and unsophisticated.

In the previous section, three aspects of military revolution were introduced: Defense, Technology, and Management. One can ask, “What is the role of e-bomb in these aspects?” The e-bomb does not have anything to do, at least directly, with the defense-management aspect. On the other hand, information warfare and network centric warfare are said to fall in the defense-technology category. As mentioned before, since the proposed e-bomb is most likely to be a major threat in future warfare (information warfare and network centric warfare), it will degrade the effectiveness of the defense-technology leg of opponent’s military technical revolution. While it degrades the defense-technology leg of the opponent’s military technical revolution, the innovation of e-bombs will be a contribution to the technology-management leg of our military technical revolution, since technology innovation, development of appropriate technology etc., falls into this category. The scenario can be vice versa. An opponent can produce an e-bomb. In this case, the countermeasures against the opponent’s move in the military technical revolution must be considered and pursued.

The next consideration of the proposed e-bomb is the role in responding to opposing military capability. Three approaches have been introduced: emulating, offsetting, and bypassing — if the opponent has taken a major innovative lead, and our country has chosen to respond. The e-bomb innovation does not fall into the emulating category (unless the opponent has developed it first). It can be an important offsetting measure, however, since it can negate the opponent’s electronic systems. On the other hand, the innovation of the e-bomb can also be considered as a kind of bypassing response — a menu that includes

developing new means of warfare to leapfrog the rival's capabilities. From this perspective, the proposed e-bomb is potentially a key element in future military rivalries.

Finally, it has been noted that improving technology in conventional weapons will be a big threat to our environment and to all humanity. This leads people to explore new ways of war that will be effective against electronic systems, but will not impact human life. Another issue is the increasing cost of conventional weapons. That is, future battles will be different, with nonlethal weapons becoming increasingly important. Nonlethality and the (relatively) low cost features of proposed e-bomb make it a reasonable and acceptable weapon of the future.

Overall, the potential effectiveness of e-bombs implies that significant military advantages will likely accrue to those who first develop and deploy such weapons.

D. THE IMPLICATION OF E-BOMB FOR THE TURKISH ARMED FORCES

The official website of Turkish General Staff defines the missions and the responsibilities of the Turkish Armed Forces as:

The Turkish Armed Forces' missions and responsibilities are clearly stated in the Turkish Constitution and determined by law. In this context, the small but flexible units, having sufficient capability equipped with technological weapons and systems, comprising sufficient command-control assets, precise and developed ammunition, covering early warning assets and also able to conduct operation in any weather conditions, are very desirable and take priority in the new approach.

To achieve this, importance and prioritization are assigned to the establishment of multifunctional units capable of conducting various tasks.

In the current political-military-strategic environment where the global and regional balances have yet not been fully formed, the Turkish Armed Forces must be capable of ensuring security of the

Turkish homeland, as well as contributing to regional and global peace and stability. Accordingly, the Turkish Armed Forces aim at maintaining or improving the following capabilities:

- deterrence of military power,
- Command, control, communication, computer, intelligence, surveillance and reconnaissance (C4ISR) systems,
- superior maneuver capability and fire power,
- Equipped with high tech weapons and systems,
- Ability to conduct operations day and night,
- Air/missile defense and NBC protection capability against the mass destruction weapons,
- Ability to conduct joint and combined operations,
- interoperability with the armed forces of the allies,
- Ability to conduct various type operations such as peace support, counter terrorism, disasters relief, crisis management, small scale strikes, blockade, embargo, humanitarian aid, control of refugee flow etc. as well as conventional war (Turkish General Staff, 2008).

Multifunctionality is identified, above, as an important aspect of achieving these capabilities. The e-bomb can contribute to the required multifunctionality of the Turkish Armed Forces due to the battlefield effects of the e-bomb. Other issues, such as increasing capability of C4ISR systems, having high-technology weapons and systems, and counterterrorism, are also directly affected by the capabilities offered by the proposed e-bomb.

The implication of the proposed e-bomb for the Turkish Armed Forces should be fully assessed in accordance with the missions and responsibilities defined in the Turkish Constitution.

1. Support Strategic/Operational/Tactical Levels of War

In the near future, a significant challenge for the Turkish Armed Forces is to define a doctrine for using electromagnetic bombs and determining how it can best be incorporated into current systems and methods. It has been shown that the e-bomb is capable of creating effects across strategic, operational, and tactical levels of war. The benefits of this integration might lead to more effective strategies and tactics for the Turkish Armed Forces.

The proposed e-bomb can be a revolutionary technology. Tactically, such weapons can disrupt or disable an opponent's electronic assets. Even though the effective weapon's radius is limited up to 10-20 km, e-bomb range can be enhanced up to 150-200 km with appropriate missile design. This will add new combat capability to small and flexible Turkish units. As a result, tactical aircrafts (manned or unmanned) equipped with e-bombs, are likely to be more capable than units equipped with traditional conventional weapons systems.

At the operational and strategic levels of war, the Network Centric Warfare and Information Warfare will play an important role for both allies and opponents. A weapon like the proposed e-bomb, which can be used against the enemy's operational and strategic command assets, will accordingly be an important weapon.

Likewise, when it is getting more and more difficult to separate the "good" and "bad" people, the nonlethality of e-bombs could help Turkish Armed Forces undertake peacekeeping missions while minimizing impact on human life. In addition, e-bombs can minimize the numbers of weapons employed while decreasing the collateral damage. This allows the administration of effective strategic strike operations against buried targets or targets that are located in civilian-populated areas.

2. Homeland Security

Mobile e-bombs, which deliver their power into the enemy's system at the speed of light, might also increase the defense capability against fast moving and maneuvering multiple targets that threaten the Turkish borders by decreasing their reaction time to the e-bomb. When the terror threat is considered, and simplicity in design allows terrorists to build such weapons, Turkish Armed Forces should consider the e-bomb as a threat to homeland security and develop new defensive concepts.

Turkey's geostrategic position requires the Turkish Armed Forces to react fast and engage rapidly against multiple targets. E-bombs might give both the area coverage and precise accuracy to prevent hostile attacks on the Turkish borders.

3. Low Operational Cost

The major problem of developing next generation conventional weapons is the increasing cost for production and supportability. This may also be a problem that the Turkish Armed Forces face. Although research and development of an e-bomb requires major investments, the costs in production and operating & support phases of proposed e-bomb might be quite less than for conventional weapons. *"For example, in the case of a defense against missiles, shots from directed-energy weapons might cost around \$8,000, whereas conventional missiles could cost hundreds of thousands of dollars or even millions of dollars, depending on their types"* (Deveci, 2007). This provides a great advantage in life cycle cost while providing same effect on enemy's electronic systems.

4. Superior Information Warfare

The e-bomb has potential to be a major threat against the electronic systems that are key elements in information warfare (Figure 65). The use of

e-bombs may give the Turkish Armed Forces the capability to limit its enemy's ability to control and command their military forces.

Turkish Armed Forces could use the e-bomb to attack and disable enemy aircraft, ground and air control systems, communication devices, radars, and air defense systems. In addition, it may be used to attack enemy commercial radio and television stations, which make anti-propagation, to limit their information network capabilities.

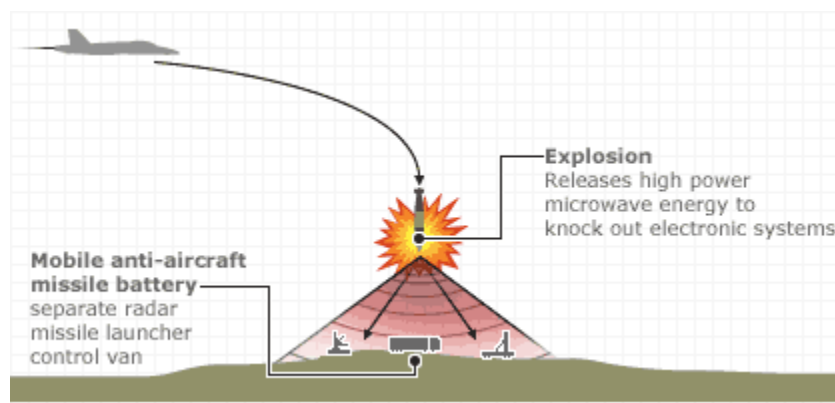


Figure 65. Damage and Destroy Enemy Information Systems (Deveci, 2007)

5. How E-Bombs Benefit Turkish Land Forces

E-bombs may change capabilities of the Turkish Land Forces both defensively and offensively. Any Turkish Land Forces unit equipped with an e-bomb might engage in a new way of war — with significant operational advantages over nations equipped with conventional weapons only.

Communications and command systems are key elements in C4ISR systems for land warfare as well. Such systems are one of the first targets attacked in order to limit the opponent's operations. The Turkish Armed Forces could use e-bombs to mount an effective attack against an enemy's C4ISR systems.

Integrating e-bombs into the existing land warfare doctrine might also increase the accuracy and volume of the Turkish Land Forces' fire in more complex and diverse environments. As seen from the latest land warfare developments, the probability of fighting in urban areas is increasing. Because civilian involvement and collateral damage are also increasing, conventional weapons in such an environment might be hard to use. This leads to increased importance for precise and tunable weapons. Turkish Land Forces may use the proposed e-bomb, with its nonlethality feature, against a wide range of targets.

E-bomb-equipped helicopters or unmanned air vehicles (UAVs) could provide close air support for the Turkish Army. In this aspect, such platforms might target critical command, control, and communication (C3) capabilities, sensors and weapon guidance systems.

The Turkish Land Forces will remain an important component for the national strategy and when enhanced with proposed e-bombs, equipped Turkish Land Forces units would gain a decisive advantage over other nations' armies, which do not take the importance of this future weapon into account.

6. How E-Bombs Benefit Turkish Naval Forces

Turkey is bordered on three sides by seas: the Black Sea, Aegean Sea, and Mediterranean Sea. This makes the sea power a critical component of national security. Being equipped with proposed e-bomb could enhance the Turkish Naval Forces' ability to execute its missions.

Some of the possible threats for today's naval forces have been defined by the Royal Institution of Naval Architects as:

- *Aircraft attack*
- *Ship-based or land-based helicopters*
- *Ship-based or land-based UAVs*
- *Ship-launched or submarine-launched anti-ship missiles (ASM)*

- *Surface ship gunfire*
- *Torpedoes*
- *Mines (Royal Institution of Naval Architects, 2004)*

The greatest threat to the Turkish Naval Forces is probably anti-ship missiles (ASMs). Even though use of e-bombs is theoretically possible, it may be more complex in practice. However, the best defense against an opponent's missile-equipped platforms is to disable the delivering platform. In this aspect, the use of e-bombs may be a good defensive measure since it can degrade the effectiveness of ASM delivering platforms such as aircraft and ship-based/land-based helicopters. In addition, the defense of a ship will be limited to several threat/missiles. That is, if the enemy attacks with more than that number at the same time, the ship will not be able to react/defense against all of them. In such a scenario, the e-bomb may provide great advantage as well, since it makes more difficult the orchestration of saturation missile attacks. In addition to these threats, the most susceptible segments of naval ships are high-technology communication, sensor, and navigation systems. The proposed e-bomb may also be a new way of fighting against these systems aboard enemy ships.

In the maritime environment, e-bombs might have limitations due to the limited speed of naval ships. The employment of e-bombs on missiles seems the best solution for naval ships. This requires e-bombs loaded onboard. The complexity of coupling and potential lethality may preclude e-bombs being a superior alternative to conventional weapons.

However, the implication of e-bombs for Turkish Naval Forces may well provide extraordinary advantages as long as their inherent limitations are well understood. A combination of both e-bombs and conventional weapons is likely the best solution for the Turkish Navy.

7. How E-Bombs Benefit the Turkish Air Forces

Turkish Air Forces seem to be the component of the Armed Forces on which the proposed e-bomb might have the greatest impact – in both the air-to-air battle and the air-to-ground battle.

The number of missiles that an aircraft can carry limits air-to-air engagements (Thompson and Goure, 2003). Instead of having a limited payload, e-bomb-equipped Turkish fighter aircraft might be effective against numerous air targets. This is likewise a major advance in Suppression of Enemy Air Defense (SEAD) operations. In the beginning of any war, defeating opponent's air defense system is highly important. The anti-radiation missile is commonly used by the aircraft in such operations. Since an e-bomb has the potential to defeat multiple air defense systems, the capability gained by the e-bomb would be a major development for Turkish Air Forces.

The advantage of e-bomb gained for air-to-air battle is similar to that for Turkish Naval Forces. When there are several aircraft as a threat, the multiplier effect of the proposed e-bomb would enhance capabilities to defeat the threat. In addition, the speed and maneuver limit for the Turkish Naval Forces can be compensated for through the much greater speed of Turkish Air Force assets. This makes different e-bomb employment methods such as bomb, glide bomb, etc., useful for Turkish Air Forces aircrafts.

As mentioned before, e-bombs are not yet mature, but they offer increasing capabilities for all levels of war. The country that can explore the benefits of such weapons and make investments in research can reap important advantages against military rivals. Therefore, it is time to seriously consider committing more effort to research and development of the e-bomb.

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VI. CONCLUSION AND RECOMMENDATIONS

Victory is for those who can say, "Victory is mine." Success is for those who can begin saying, "I will succeed," and say, "I have succeeded" in the end.

— Mustafa Kemal Atatürk, The founder and the first president of the Turkish Republic

The directed-energy weapons have matured in many areas and are considered a major technical revolution in the twenty-first century. Such weapons are expected to play an important role in the battlefield of the future, both in defensive and offensive aspect. The hypothetical e-bomb that is proposed in this study is introduced as one of the directed energy weapon of the future. The proposed e-bomb is intended to be used as an offensive weapon rather than a defensive weapon.

In this thesis, three classes of the hypothetical e-bomb were proposed, and a theoretical simulation was generated to show the characteristics of each hypothetical e-bomb. The high-power microwave theory was used to simulate such weapon. The simulation results showed that such weapons are able to generate power levels that are more than known upset or permanently damage levels of electronic devices and systems when used against appropriate targets. The coupling of generated field strength into the target is more complex than the way explained in this study and depends on many parameters. However, a basic coupling estimate showed that the hypothetical e-bomb has a militarily reasonable potential lethality range depending on shielding effectiveness of the targets.

Another interesting result of the simulation is that commercially available technology for such a weapon is sufficiently mature to be a significant threat in many areas. Especially, low-tech and medium-tech e-bombs involve devices that

can be found easily and do not require deep engineering knowledge. This makes such weapons quite interesting for everyone. Once the terrorists explore these weapons and the simplicity of them, the asymmetric threat of the future will probably have new dimension.

There are still some issues which must be addressed in the designing and application of such weapons and engineering research must continue to overcome these challenges. Such research include simplifying the complexity of hypothetical e-bomb, decreasing the size, increasing power, and finding the most appropriate delivery method that gives maximum range. However, the development of e-bomb for military applications is expected to continue, and, in the near future, countries will implement this weapon in compact sizes and will develop new defensive concepts against such weapons.

In this study, including the technical aspect of hypothetical e-bomb, the effectiveness and the role in military rivalry were assessed as well. A measure of effectiveness model was developed in order to compare electromagnetic weapons. The model results showed that the proposed e-bomb has a potential to be as effective as HEMP that is known as “the nuclear bomb for electronic devices.” Since there is no e-bomb officially reported in open literature and not enough qualitative data to compare such weapons, the proposed measure of effectiveness model mostly depends on the qualitative measures defined by the author of this study. Even though the model itself represents a good comparison model for the effectiveness of electromagnetic weapons, it surely needs more quantitative data to be more realistic. Future development in this area and data that can be obtained after the implementation of such weapons in the battlefield will provide enough data that is required to make more realistic effectiveness comparison. In addition, there is not open literature that provides cost data for such weapons. Again, when the cost data is obtained in the future, or a reasonable cost estimation for such weapons is made, more realistic cost-effectiveness analysis will provide a better approach for the decision makers. However, one can sense that the e-bomb will be less expensive than other

electromagnetic weapons because of its size and technological simplicity. This makes the hypothetical e-bomb an attractive area for research and development investments.

As mentioned in the previous chapter, the Turkish Armed Forces will remain committed to the development and deployment of technologically advanced systems to be ready for the uncertainties of future battlefield. In this aspect, the special features gained by the proposed e-bomb will clearly be a force multiplier and provide opportunities to improve the Turkish Armed Forces' operational capabilities in diversity of mission areas. This will lead the Turkish Armed Forces to take advantage in military rivalry. On the other hand, failure to develop and understand the proposed e-bomb might be a big threat for the Turkish Armed Forces in the future since the threat will be a new unknown face of future battlefield. In contrast, this will weaken the Turkish Armed Forces' military power and war-fighting ability that results in staying behind in military rivalry.

As a result, the Turkish Armed Forces might need to explore the technological countermeasures against the potential e-bomb in the battlefield of the future before facing an opponent that is equipped with these weapons.

This thesis concludes with several recommendations for the Turkish Armed Forces as it considers the possibility of implementation of an e-bomb.

- Technological advantage gained by the proposed e-bomb might give the Turkish Armed Forces new capabilities to deal with the diverse threats in its geostrategic position. This advantage might be attained by investing in developing the proposed e-bomb.
- Referring to the mission of the Turkish Armed Forces for supporting the global peace and conducting operations for peacekeeping, the nonlethality feature of a hypothetical e-bomb might be a useful weapon since it offers a new way of war that degrades opponent's electronic systems while making no damaging harm on humans.

This might also minimize the personnel injury that is expected to be more in an operation conducted by the conventional weapons.

- Considered that future battles will involve a new ways of war such as Information Warfare and Network Centric Warfare, the Turkish Armed Forces might explore the key factors that will play an important role in this new battlefield. The research and development of a proposed e-bomb might be a beneficial investment for the Turkish Armed Forces since it offers a notable threat against command and control systems, computer systems, communication devices etc., which are the main sensors and systems in Information Warfare and Network Centric Warfare.
- With optimal cost-effective investments, the Turkish Armed Forces could establish a joint organization to research the e-bomb with the participation of the national universities and national scientific research institutes. Such organization might have overall responsibility for the engineering and production phases of these weapons, which would help to accelerate the innovation of e-bomb technology. This might also help the civilian contractors to contribute in defense business and lead similar applications in different areas.
- The increasing cost of conventional weapons is more likely to be a big problem in the future. Even though such weapons provide a big advantage on the battlefield, the expected increasing cost in production, and operating and support phases will make them difficult to maintain for the whole life cycle. The lower cost and the multiplier effect of the proposed e-bomb might be a better option that may give the same effectiveness as conventional weapons for the Turkish Armed Forces.

- The Turkish Armed Forces should improve the strategies and doctrines to fight in a directed-energy environment that involves proposed e-bombs. This would include special hardening techniques that will provide shielding effectiveness for command and control systems, important communication systems, vital data links and other strategically and tactically important systems against proposed e-bombs. As a result, this new concept would increase the survivability and recoverability of the Turkish Armed Forces in the battlefield of the future.
- The military rivalry is an ongoing event and will never be over. To be among the leading countries or to be behind other countries in the military rivalry of today does not mean that it will be the same in the future battlefield. Nevertheless, there is a reality that the leading countries who will achieve the military technical revolution in military rivalry will have the power to shape the world as they intend to do. No matter which place Turkey is located in military rivalry today, it should explore the key elements of the future battlefield to get the leading place among other countries. In the context explained in this study, the proposed e-bomb has the potential to be a part of the military technical revolution for the battlefield of the future. From this perspective, the Turkish Armed Forces should benefit from this opportunity by investing in e-bomb research and development.

In conclusion, the proposed hypothetical e-bombs offer new, relatively inexpensive, technologically possible designs that might be well worth the effort in military utility. The Turkish Armed Forces should invest in e-bomb research and development (R&D) to improve its combat capabilities in the battlefield of the future. This will enhance the capability of Turkish Armed Forces to secure the borders of Turkey against internal and external threats as well as the contribution to regional and global peace. Eventually, the proposed e-bomb will be a key

element in contemporary military-technical revolution that will shape the battlefield of the future. The sooner Turkey begins to invest in the development of an e-bomb, the better position Turkey will take in future military rivalry, and the safer it will be against internal and external threats to its homeland security and well-being.

APPENDIX A

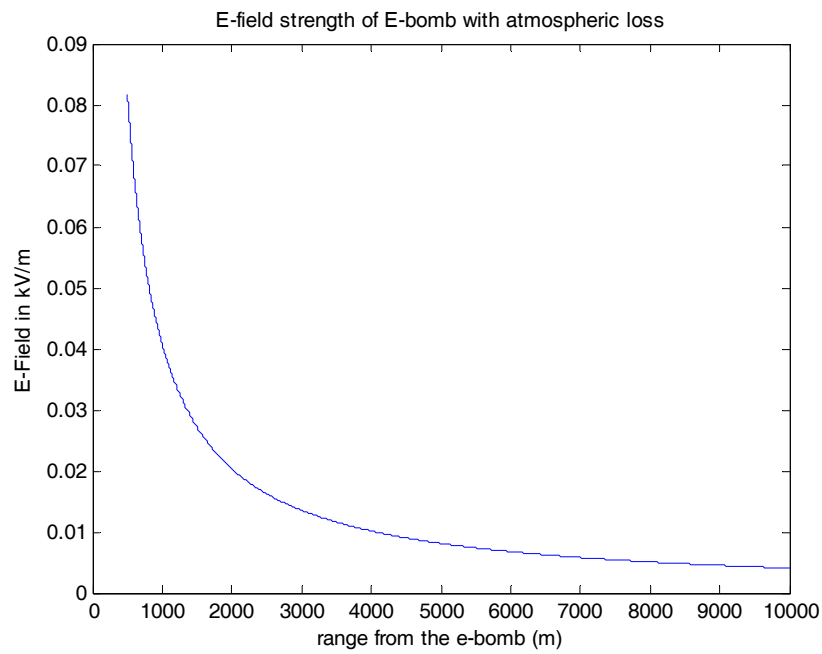
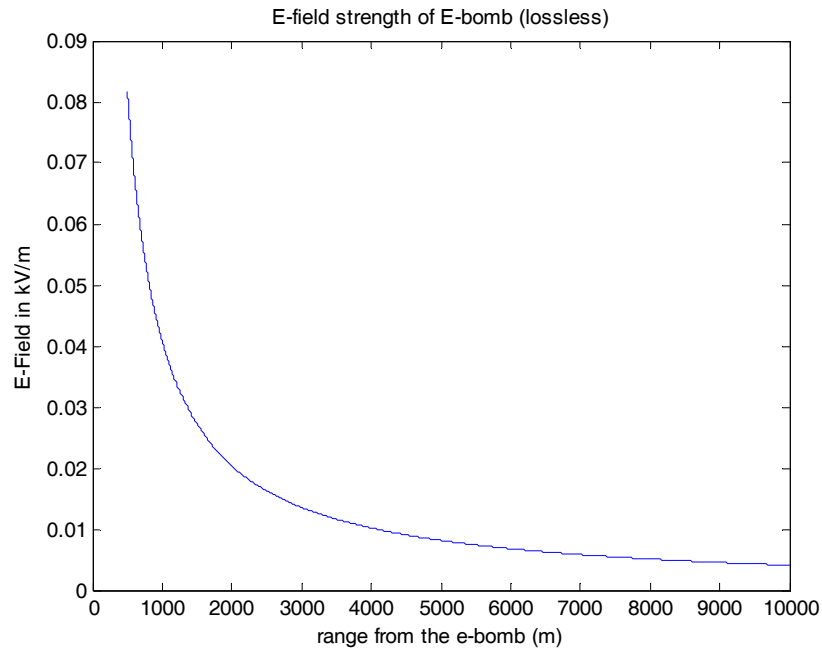
A. RECTANGULAR WAVEGUIDE SPECIFICATIONS TABLE

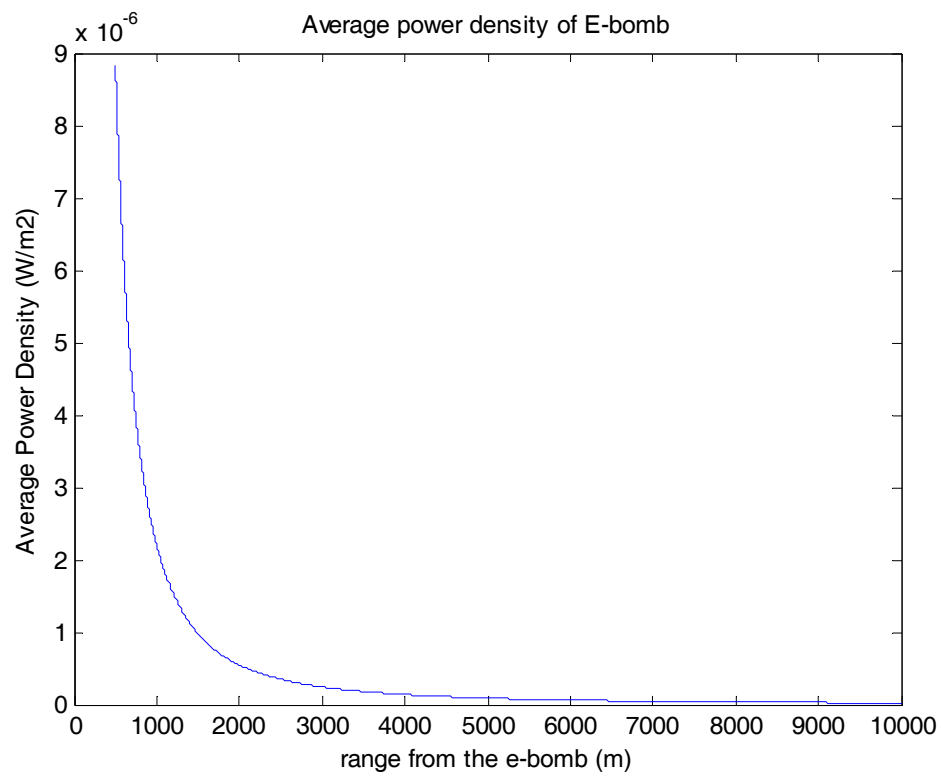
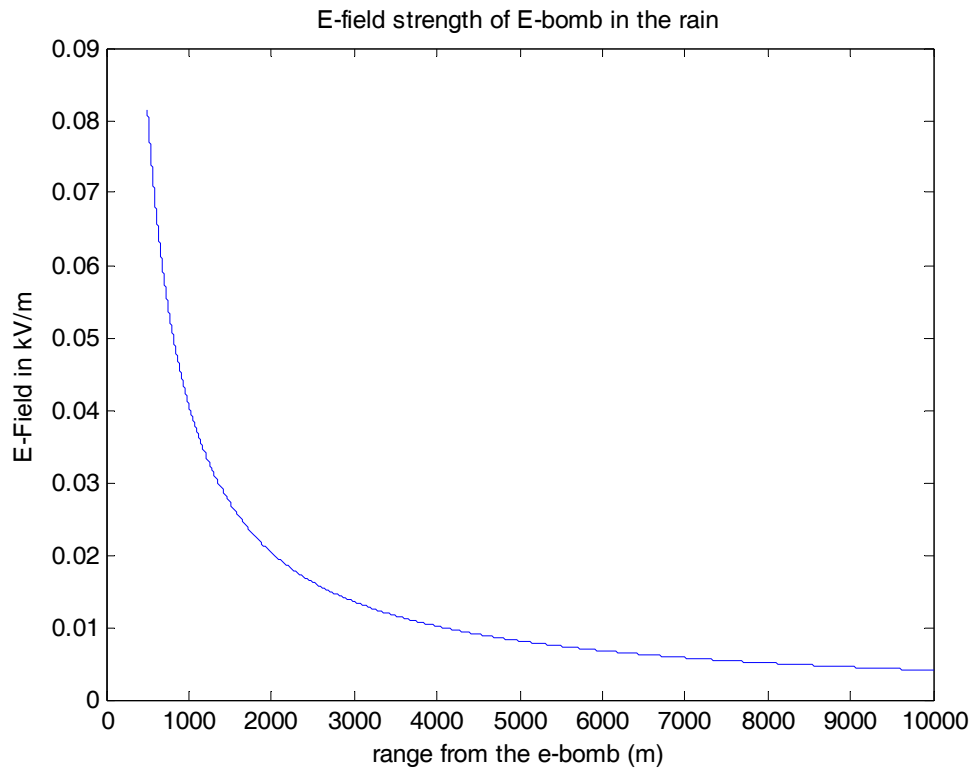
Band Design	Range (GHz)	Internal (inches)	Internal (mm.)	Official Designations		
				I.E.C.*	U.K. (RCSC)	U.S. (EIA)**
	0.32 - 0.49	23.0 x 11.50	584.20 x 292.10	R3	WG00	WR2300
	0.35 - 0.53	21.0 x 10.5	533.40 x 266.70	R4	WG0	WR2100
	0.41 - 0.625	18.0 x 9.0	457.20 x 228.60	R5	WG1	WR1800
	0.49 - 0.75	15.0 x 7.5	381.0 x 191.0	R6	WG2	WR1500
	0.64 - 0.96	11.5 x 5.75	292.10 x 146.05	R8	WG3	WR1150
	0.75 - 1.12	9.75 x 4.875	247.65 x 123.83	R9	WG4	WR975
	0.96 - 1.45	7.7 x 3.85	195.58 x 97.79	R12	WG5	WR770
	1.12 - 1.7	6.5 x 3.25	165.10 x 82.55	R14	WG6	WR650
	1.45 - 2.2	5.1 x 2.55	129.54 x 64.77	R18	WG7	WR510
	1.7 - 2.6	4.3 x 2.15	109.22 x 54.61	R22	WG8	WR430
	2.2 - 3.3	3.4 x 1.7	86.36 x 43.18	R26	WG9A	WR340
	2.6 - 3.95	2.84 x 1.34	72.14 x 34.04	R32	WG10	WR284
	3.3 - 4.9	2.29 x 1.145	58.17 x 29.08	R40	WG11A	WR229
	3.95 - 5.85	1.872 x 0.872	47.55 x 22.15	R48	WG12	WR187
	4.9 - 7.05	1.59 x 0.759	40.39 x 20.19	R58	WG13	WR159
	5.85 - 8.2	1.372 x 0.622	34.84 x 15.80	R70	WG14	WR137
	7.05 - 10.0	1.122 x 0.497	28.50 x 12.62	R84	WG15	WR112
X	8.2 - 12.4	0.9 x 0.4	22.86 x 10.16	R100	WG16	WR90
	10.0 - 15.0	0.75 x 0.375	19.05 x 9.53	R120	WG17	WR75
KU	12.4 - 18.0	0.622 x 0.311	15.80 x 7.9	R140	WG18	WR62
	15.0 - 22.0	0.510 x 0.255	12.95 x 6.48	R180	WG19	WR51
K	18.0 - 26.5	0.420 x 0.170	10.67 x 4.32	R220	WG20	WR42
	22.0 - 33.0	0.340 x 0.170	8.64 x 4.32	R260	WG21	WR34
Ka	26.5 - 40.0	0.280 x 0.140	7.11 x 3.56	R320	WG22	WR28
Q	33.0 - 50.0	0.224 x 0.112	5.69 x 2.84	R400	WG23	WR22
	40.0 - 60.0	0.188 x 0.094	4.78 x 2.388	R500	WG24	WR19
V	50.0 - 75.0	0.148 x 0.074	3.759 x 1.879	R620	WG25	WR15
E	60.0 - 90.0	0.122 x 0.061	3.099 x 1.549	R740	WG26	WR12
W	75.0 - 110.0	0.100 x 0.050	2.54 x 1.27	R900	WG27	WR10
F	90.0 - 140.0	0.080 x 0.040	2.032 x 1.016	R1200	WG28	WR8
D	110.0 - 170.0	0.065 x 0.0325	1.651 x 0.8255		WG29	WR7
G	140.0 - 220.0	0.051 x 0.0255	1.2954 x 0.6477		WG30	WR5

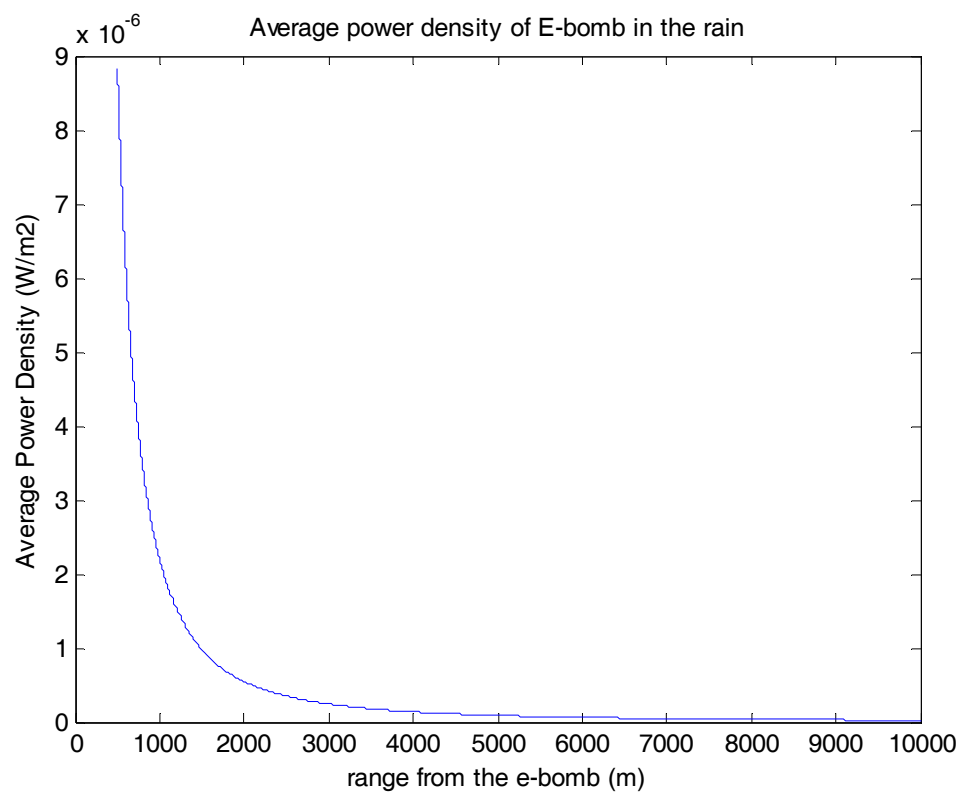
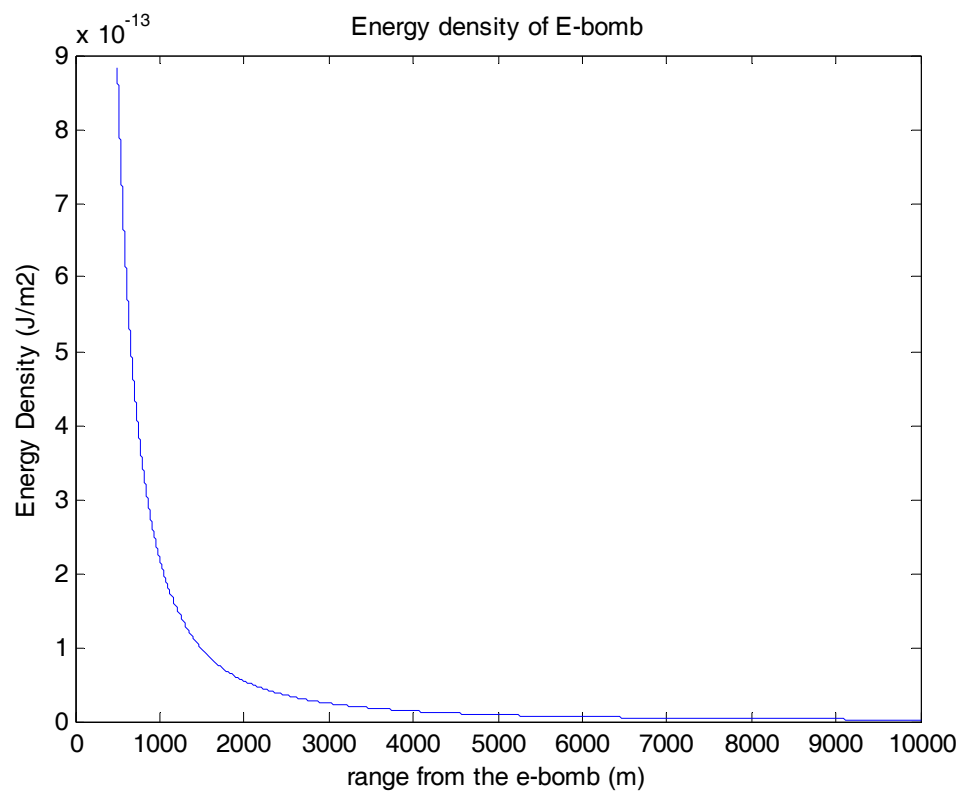
Band Design	Range (GHz)	Internal (inches)	Internal (mm.)	Official Designations		
				I.E.C.*	U.K. (RCSC)	U.S. (EIA)**
	170.0 - 260.0	0.043 x 0.0215	1.0922 x 0.5461		WG31	WR4
	220.0 - 325.0	0.034 x 0.017	0.8636 x 0.4318		WG32	WR3

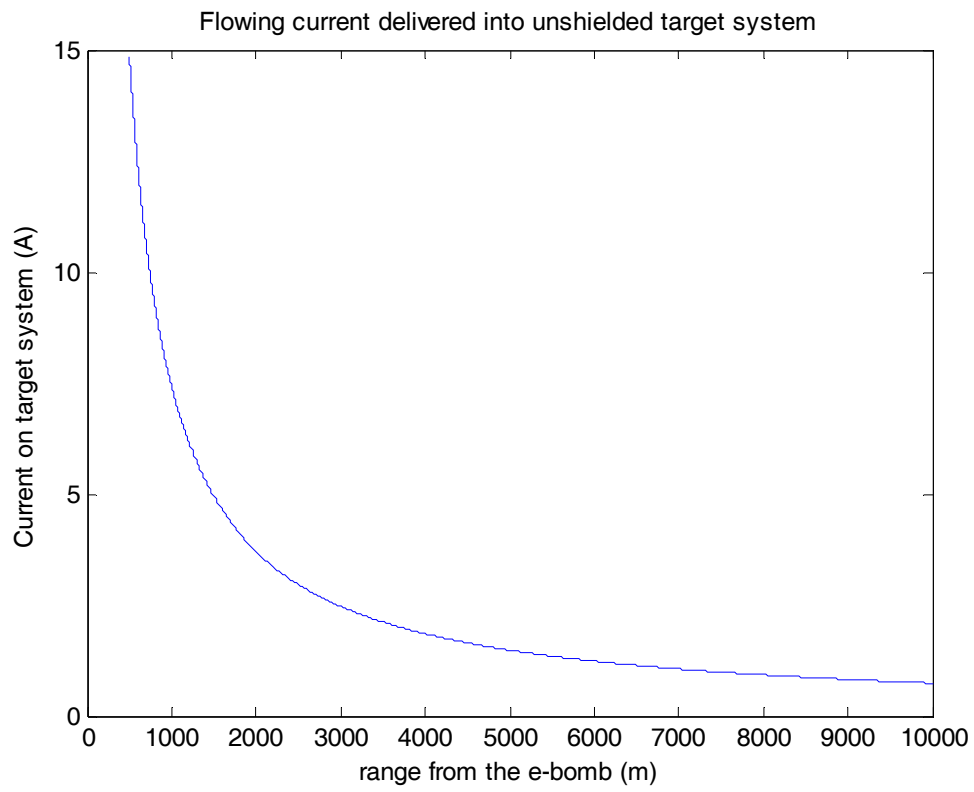
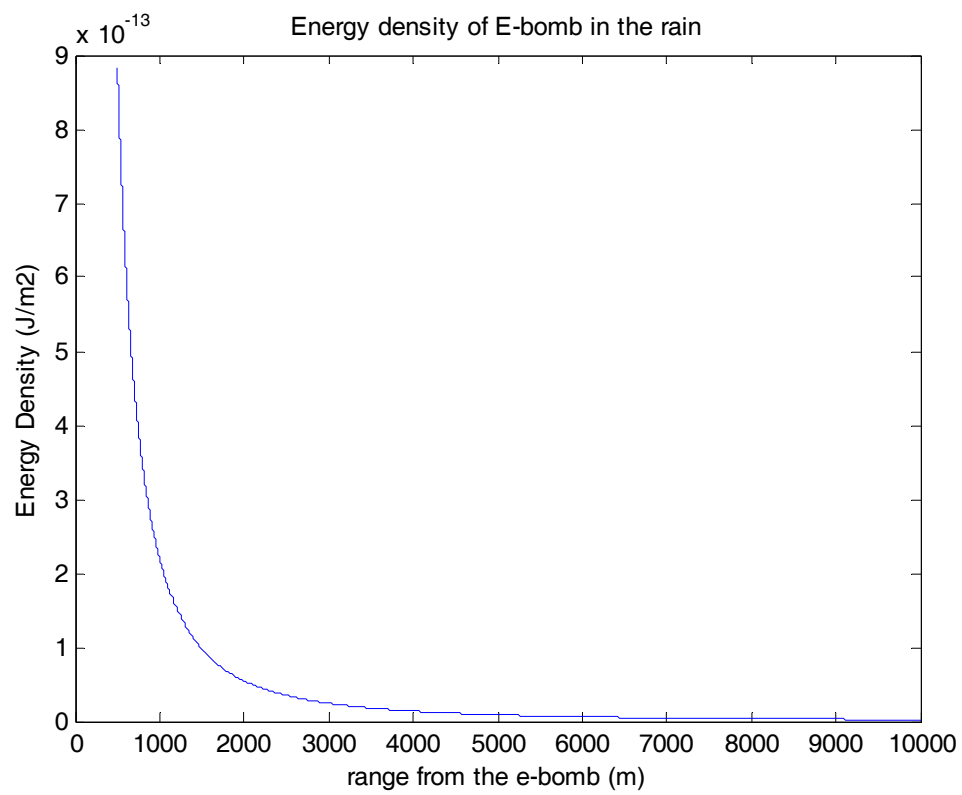
APPENDIX B

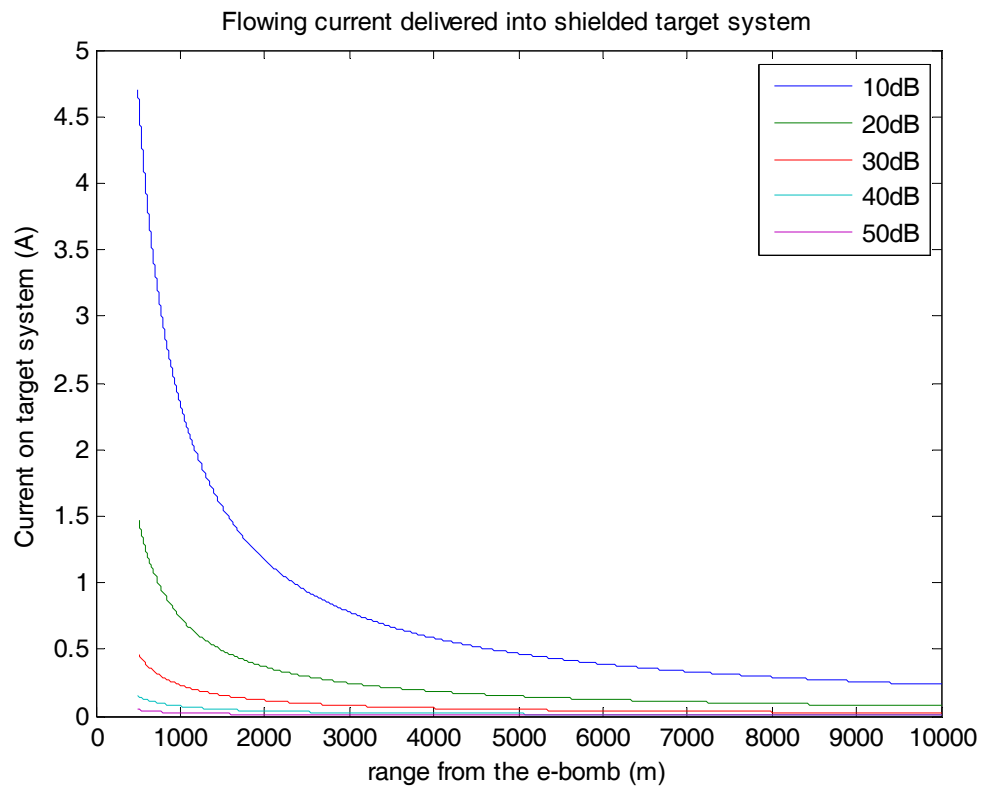
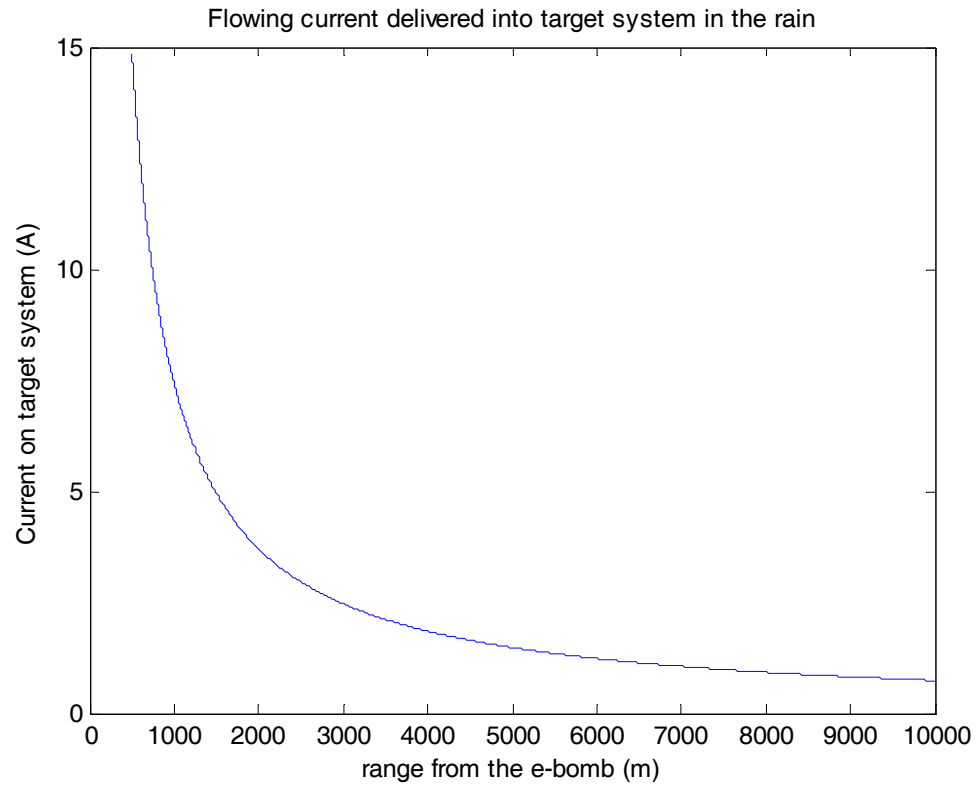
A. MATLAB SIMULATION MODEL OUTPUT PLOTS FOR LOW-TECH E-BOMB

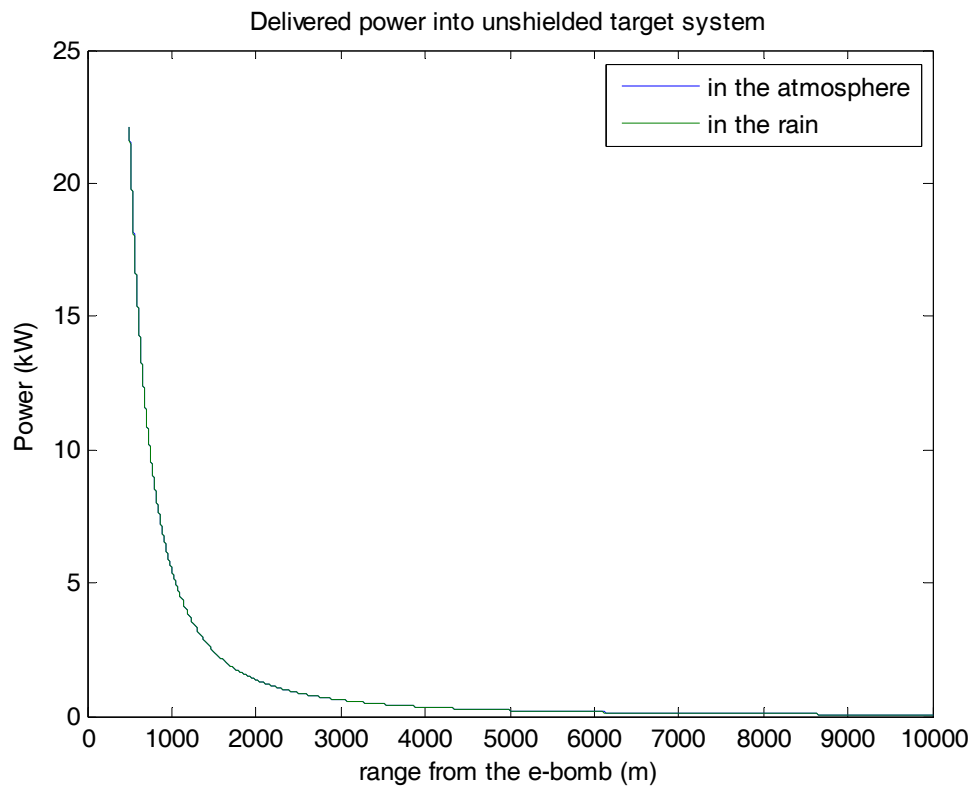
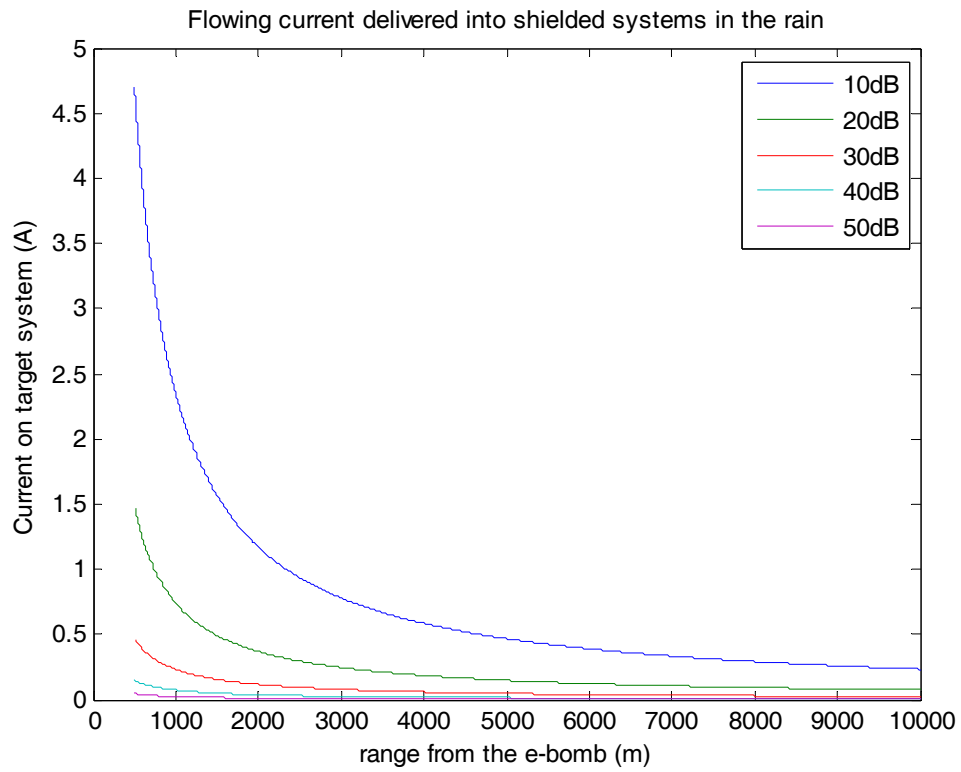


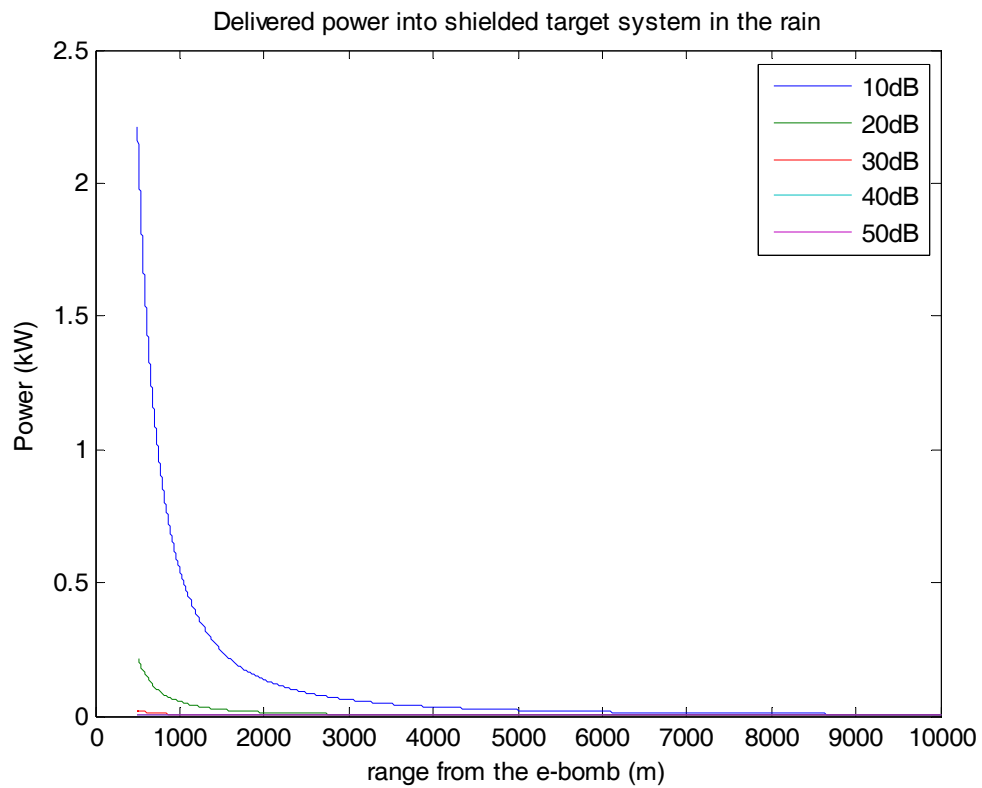
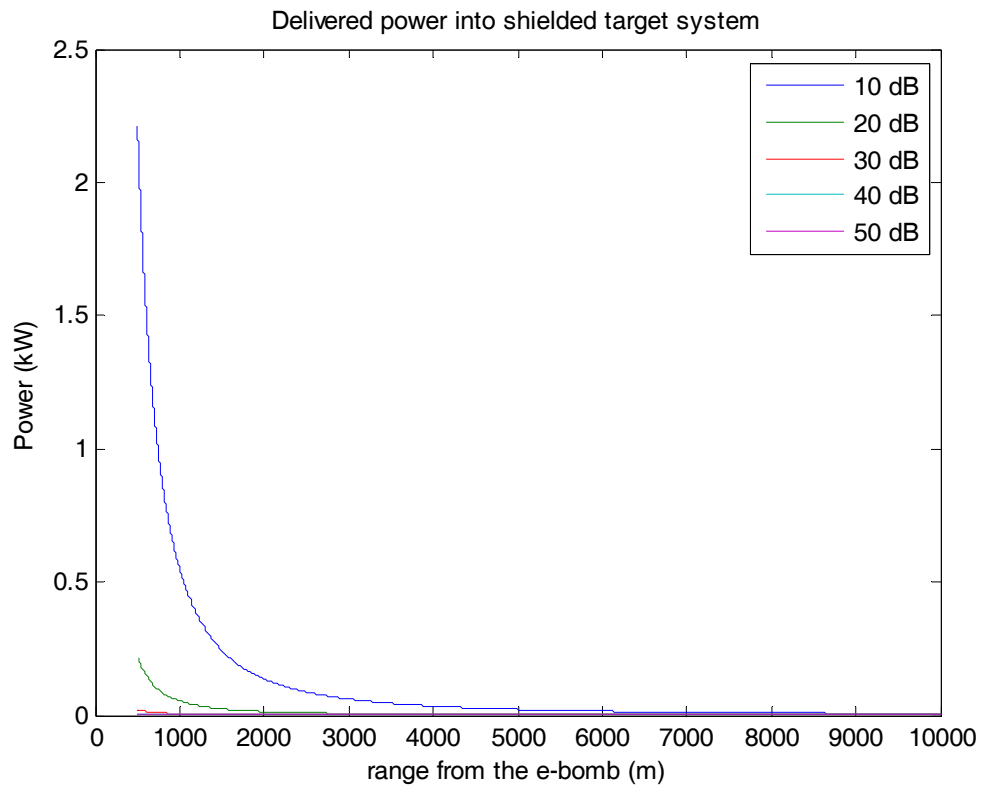




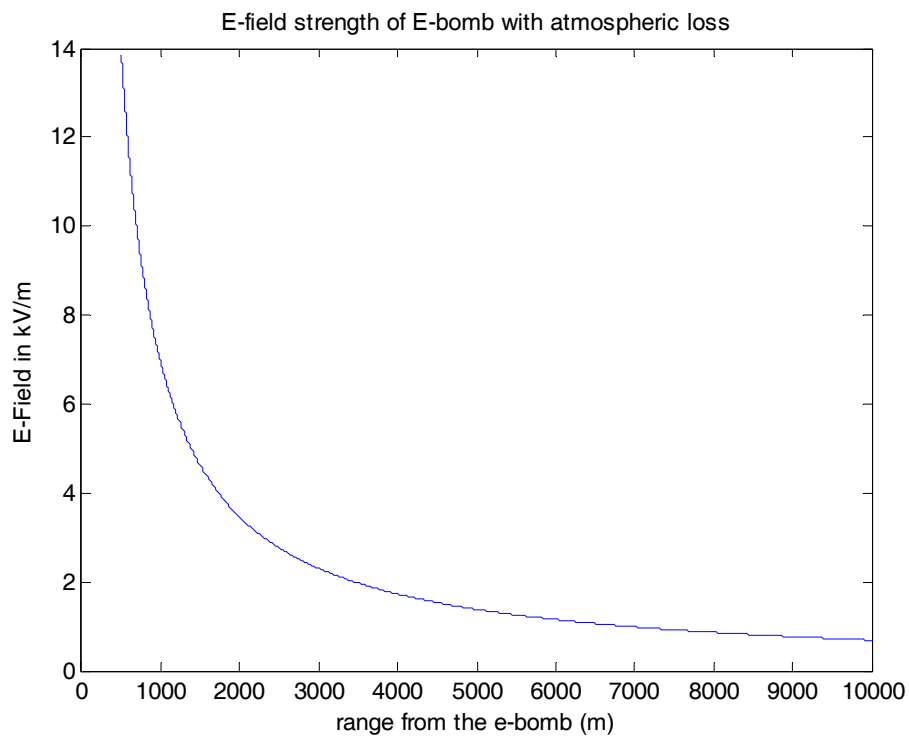
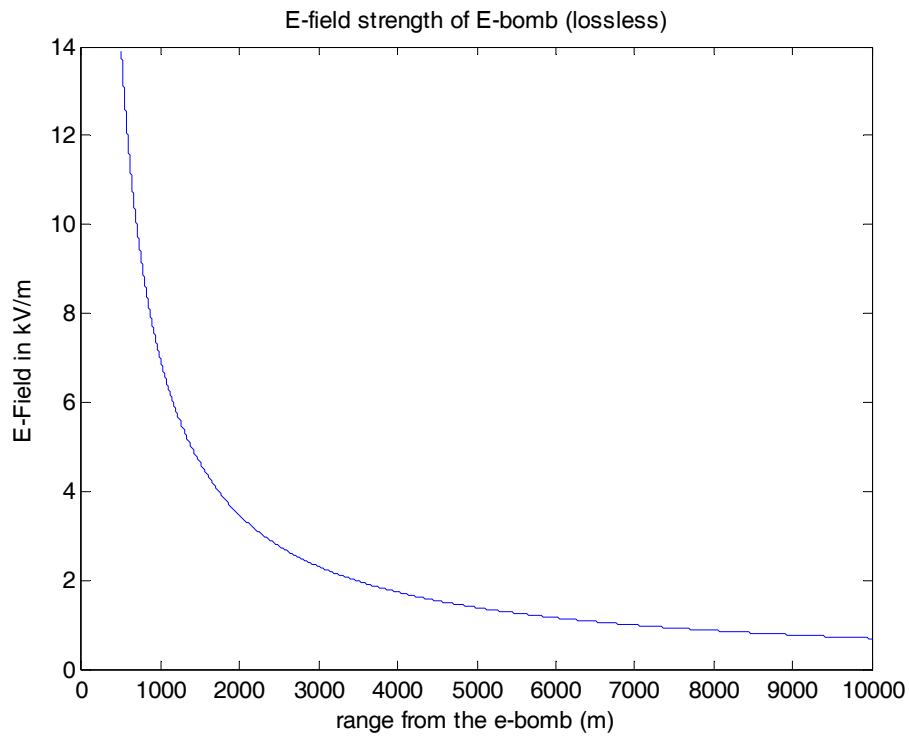


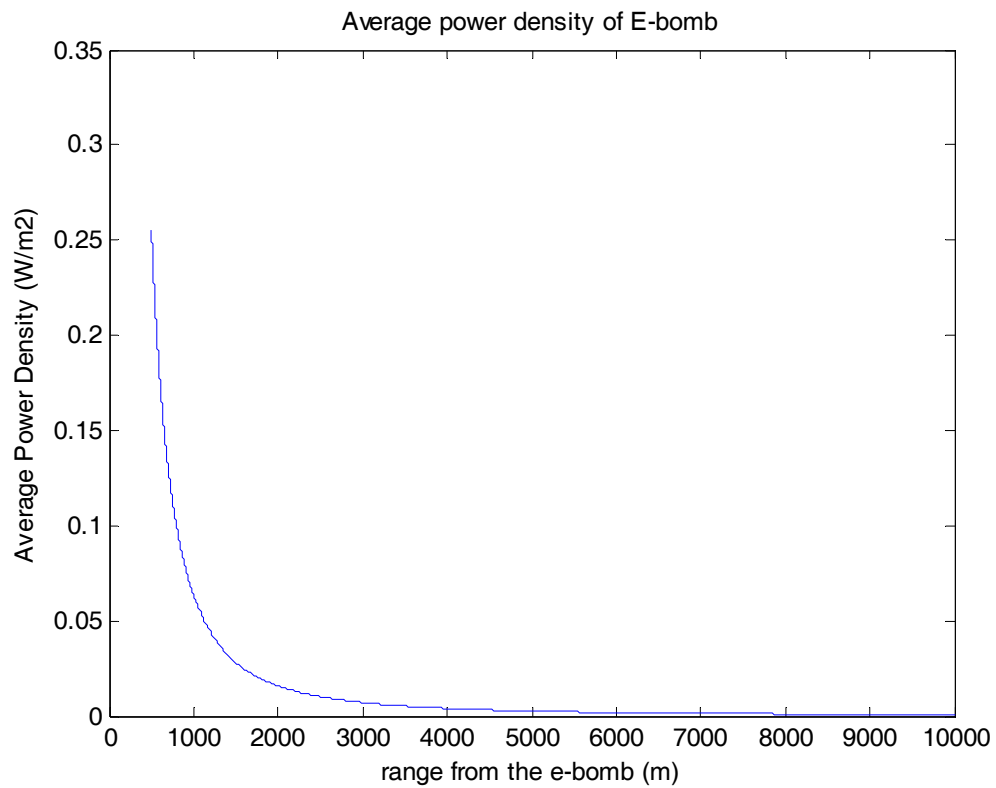
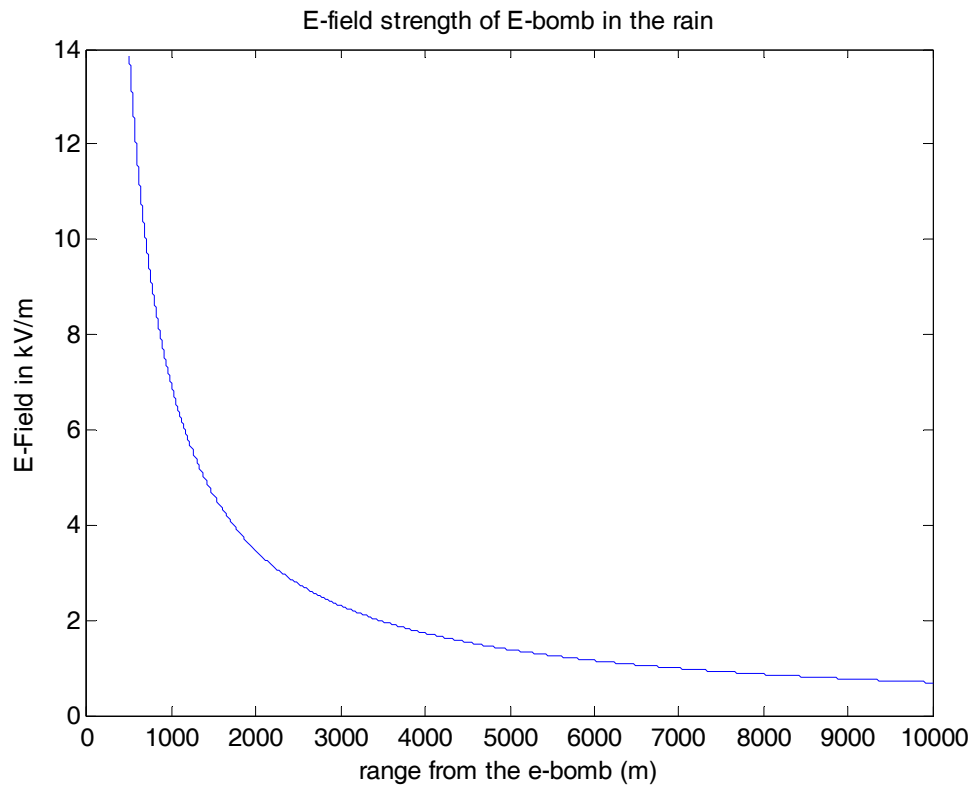


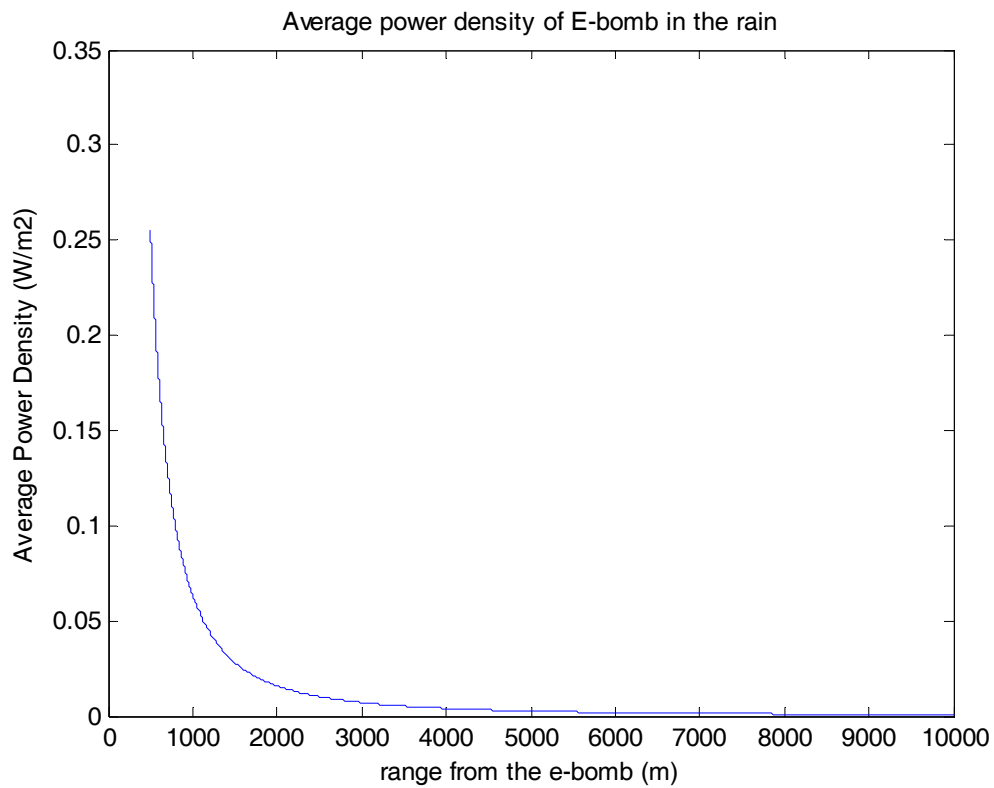
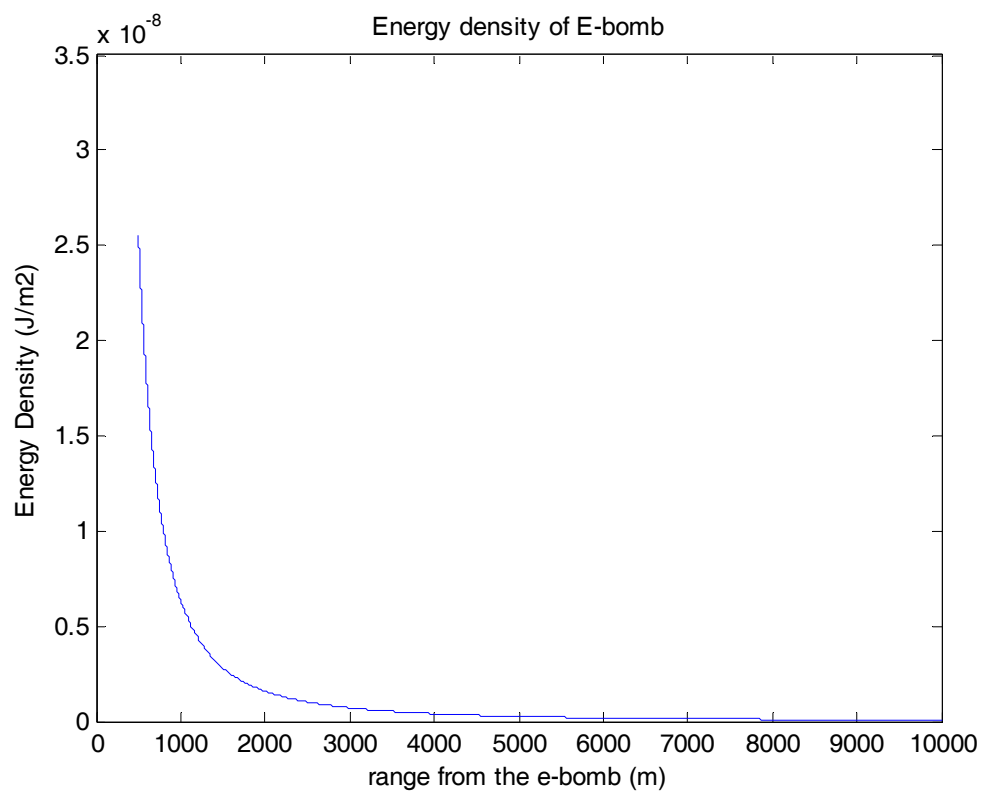


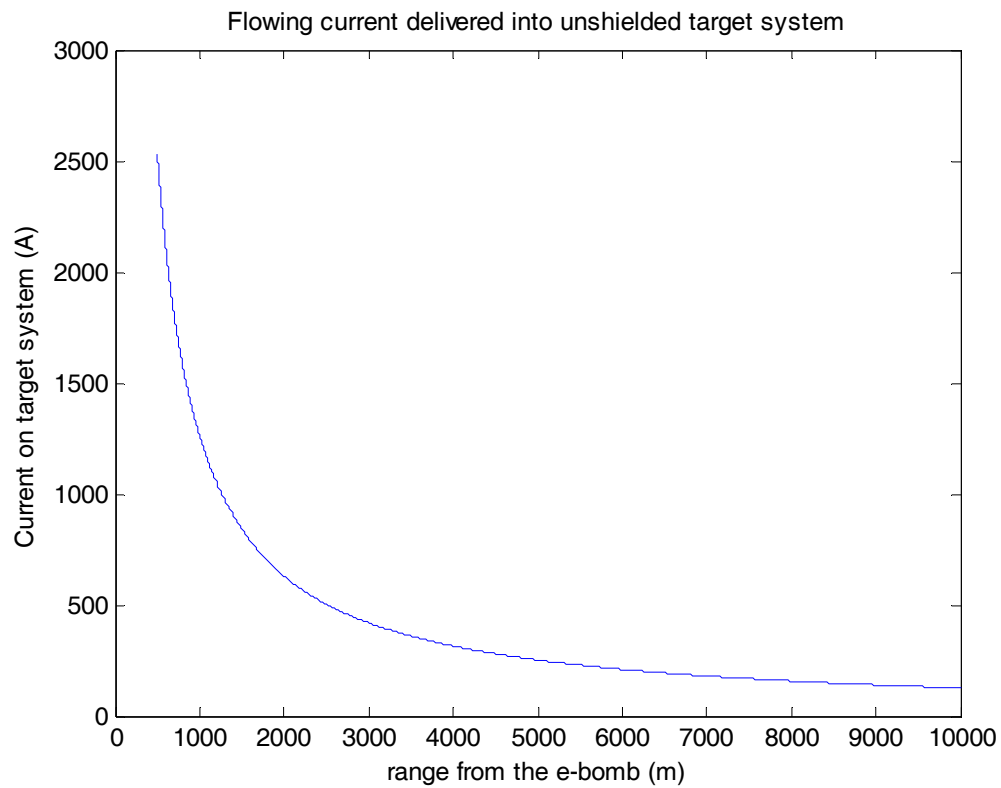
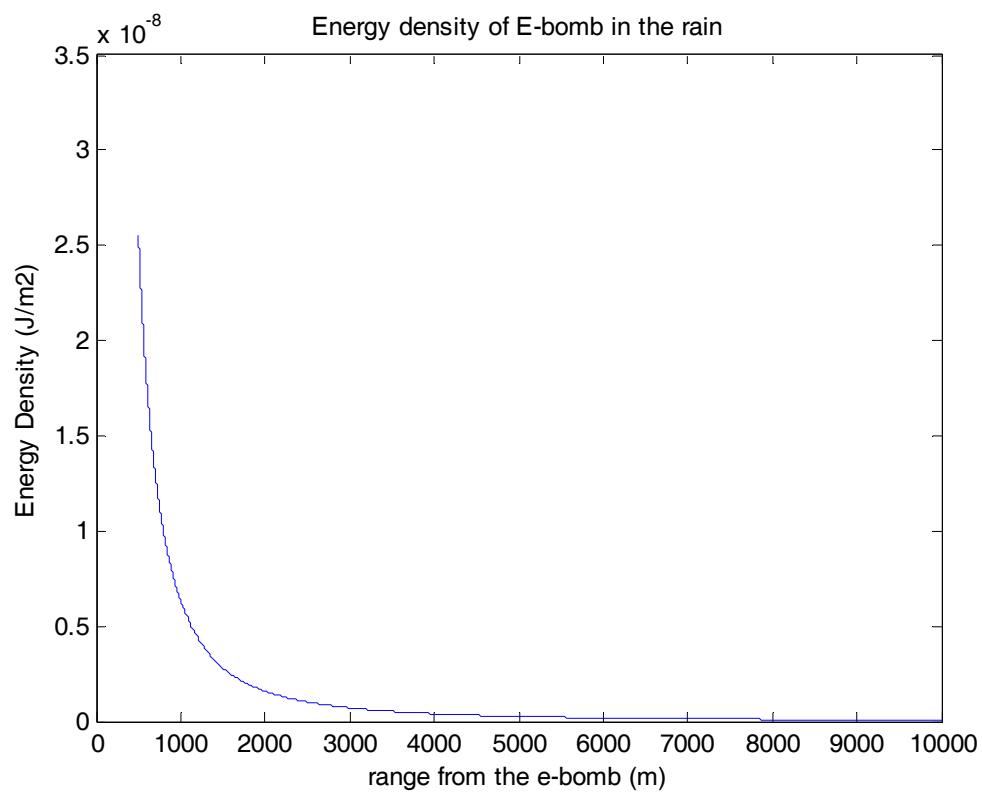


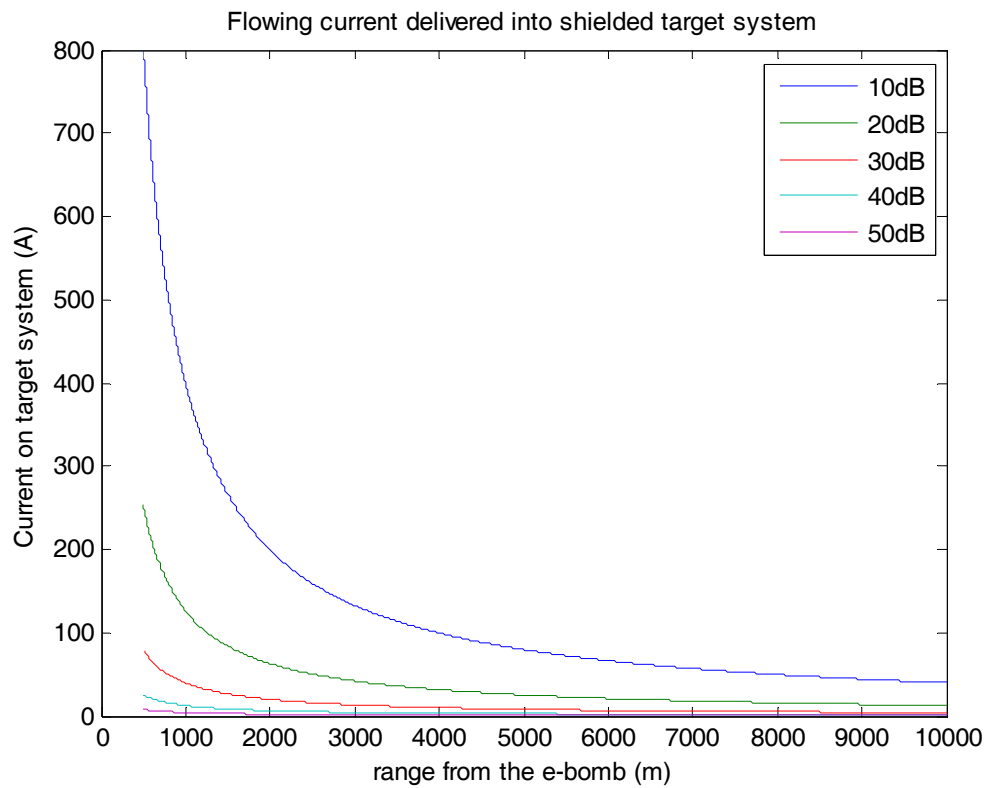
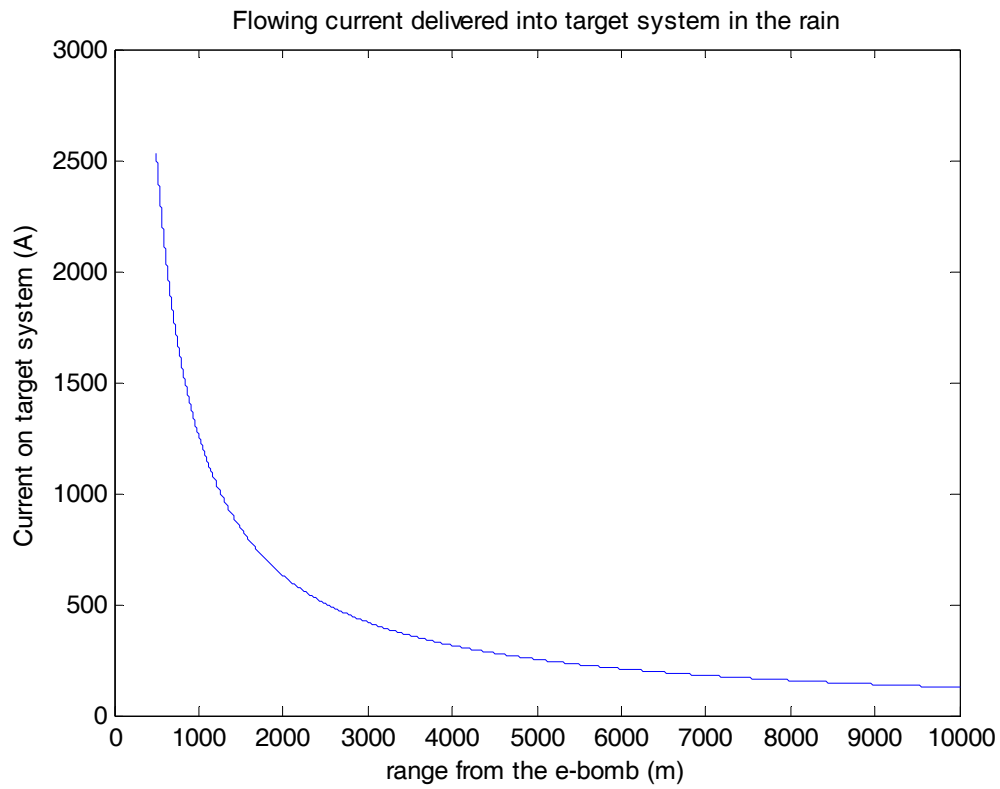
B MATLAB SIMULATION MODEL OUTPUT PLOTS FOR MEDIUM-TECH E-BOMB

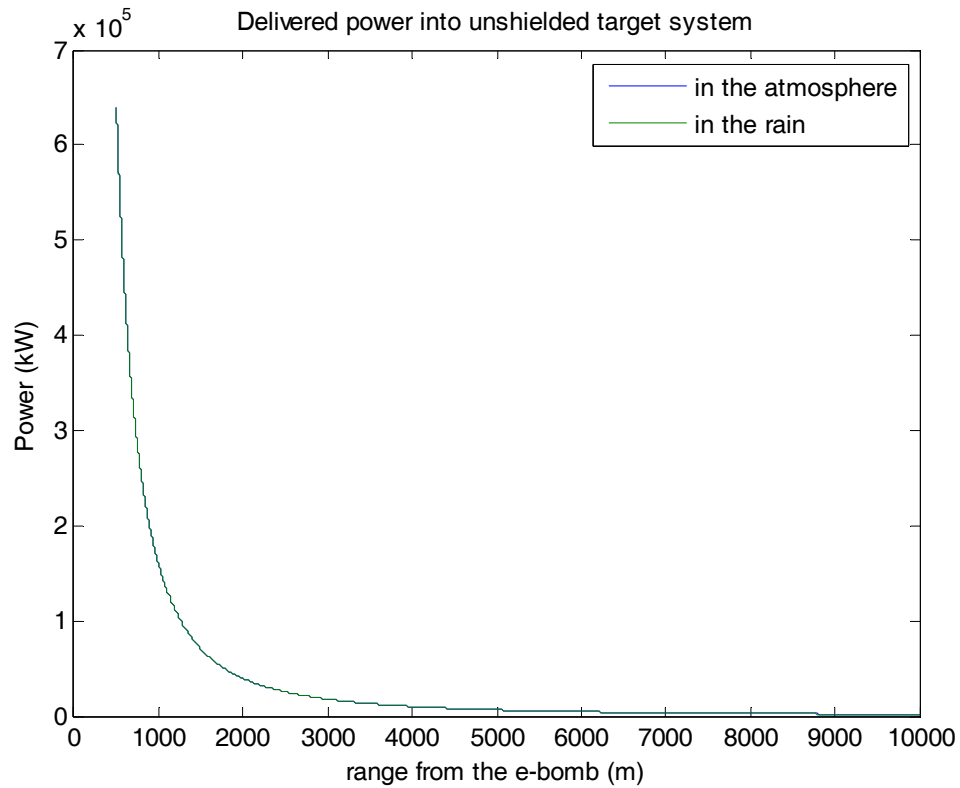
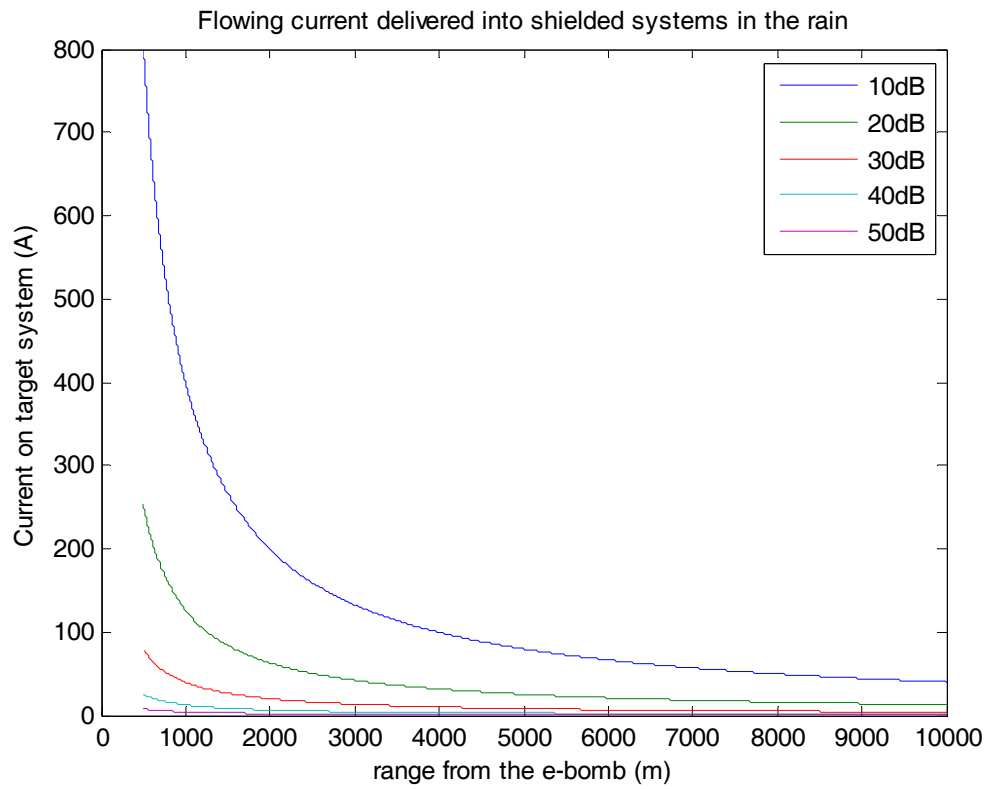


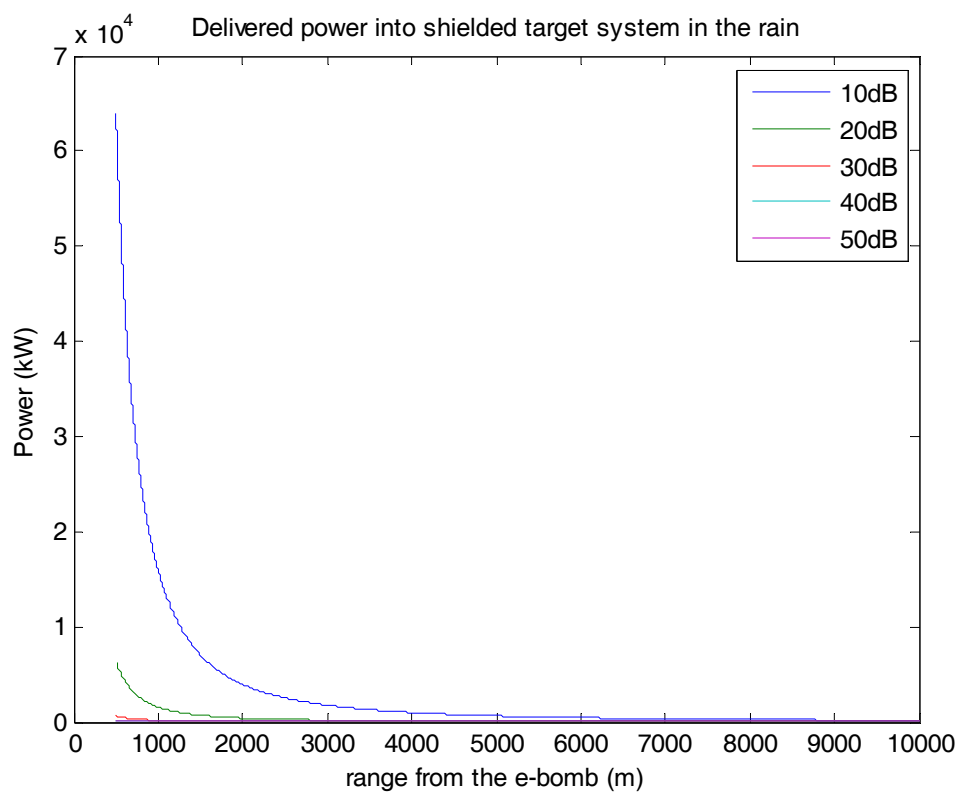
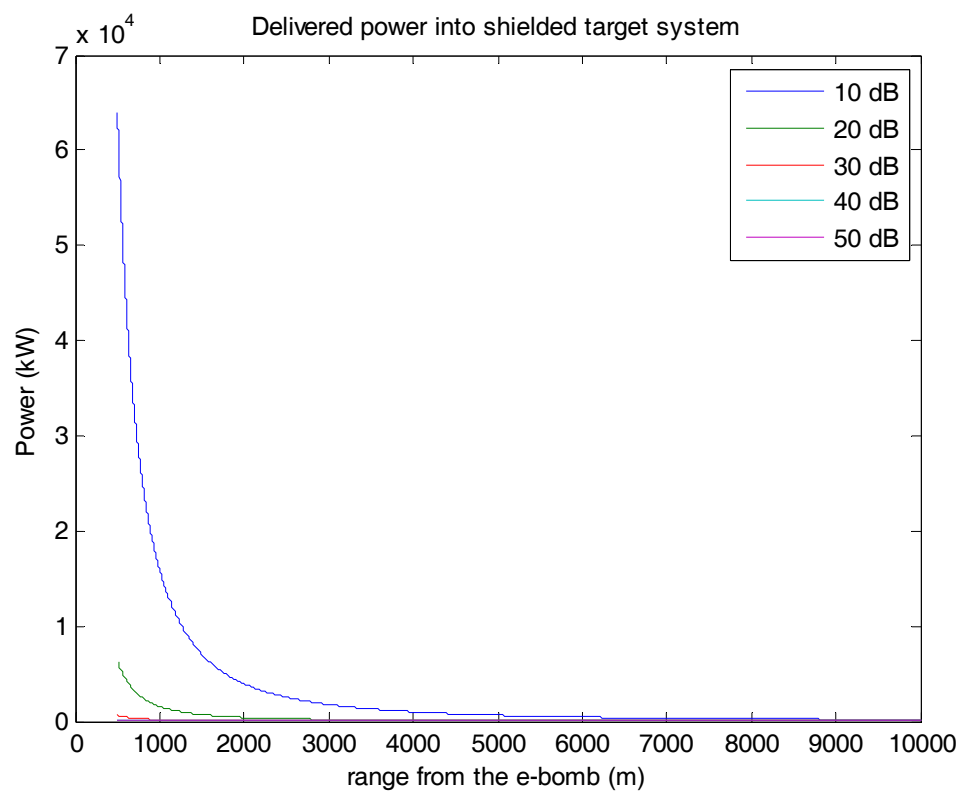




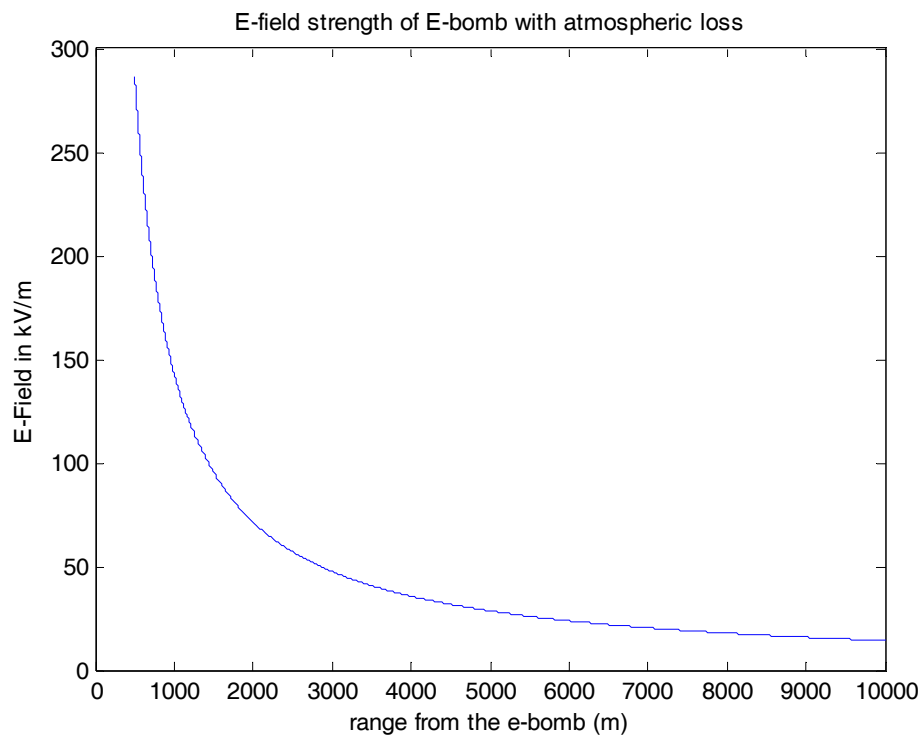
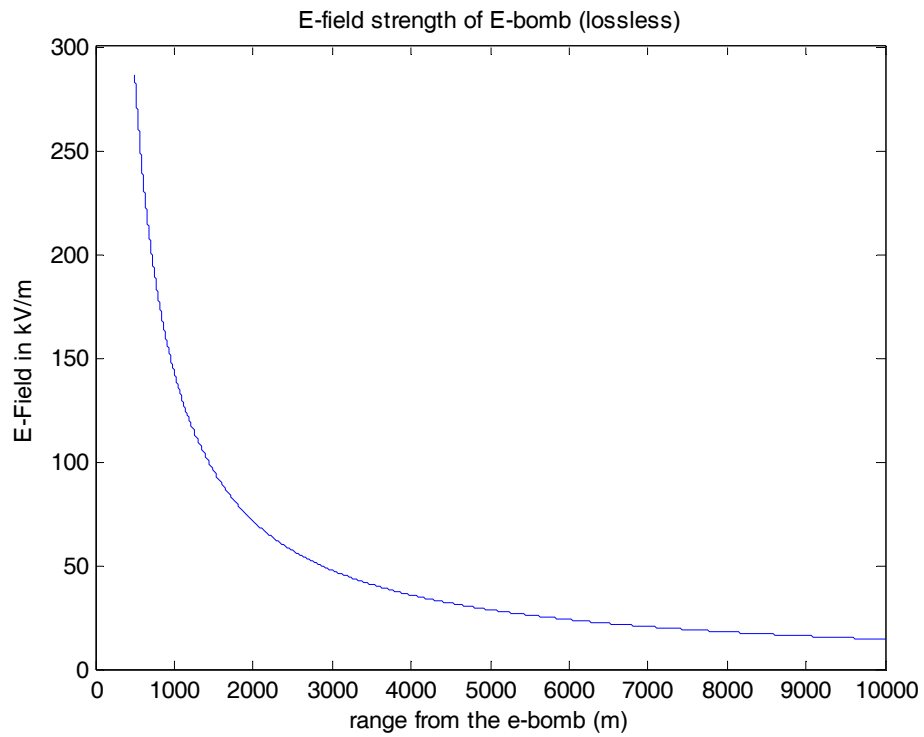


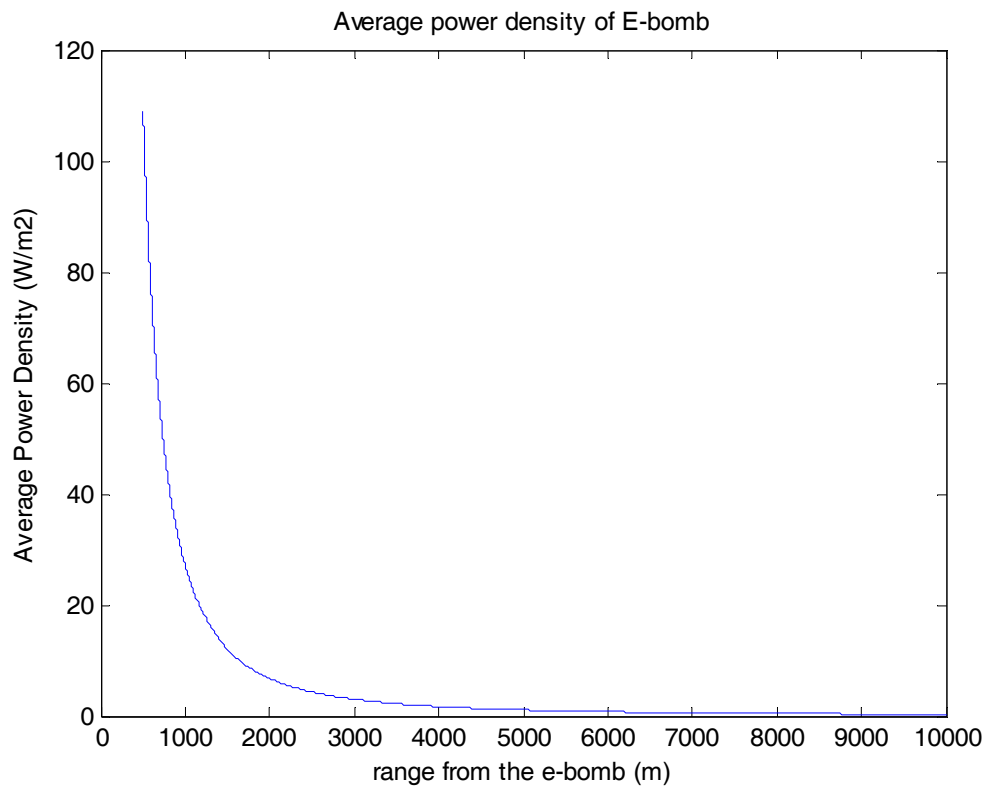
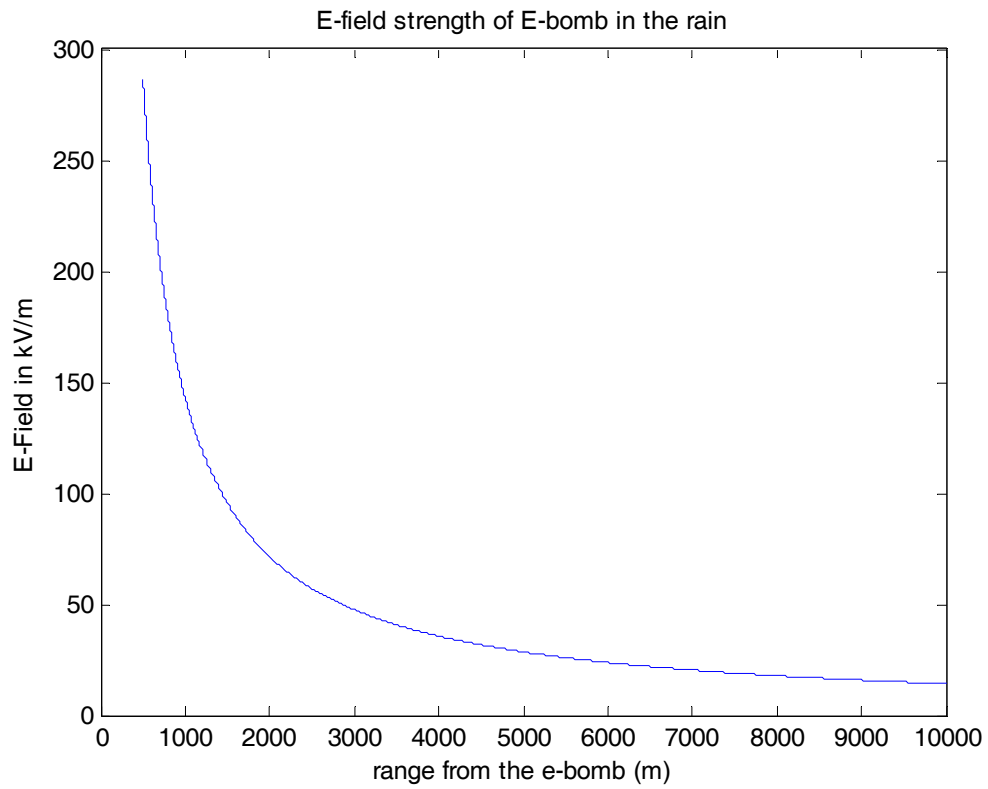


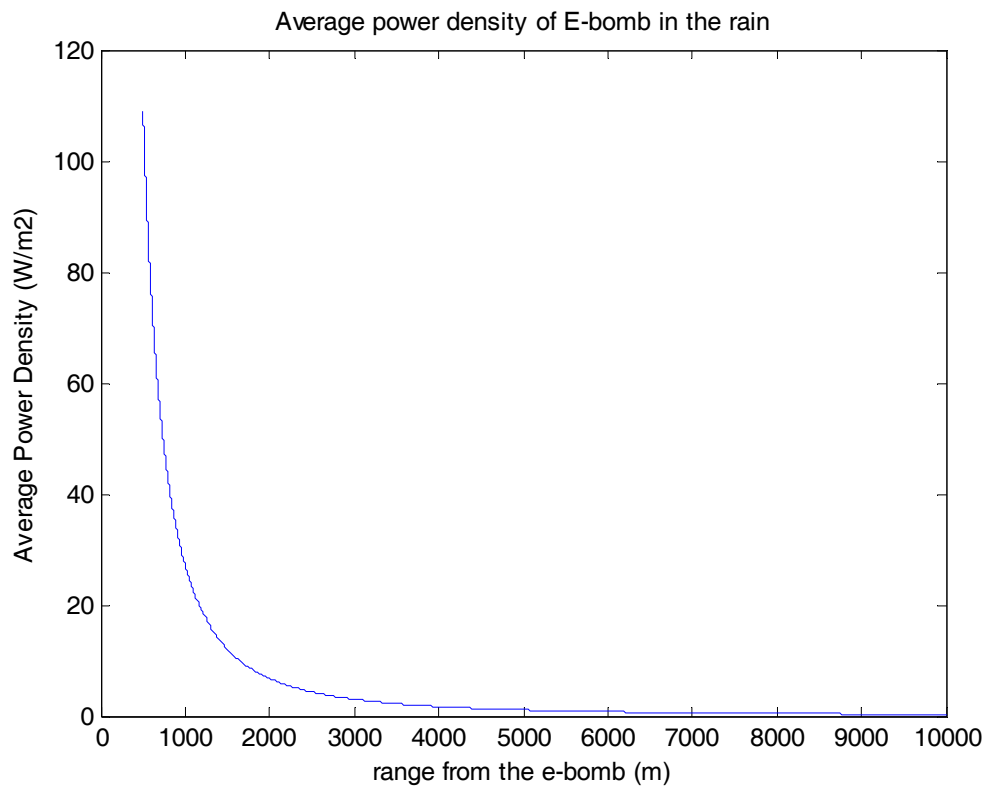
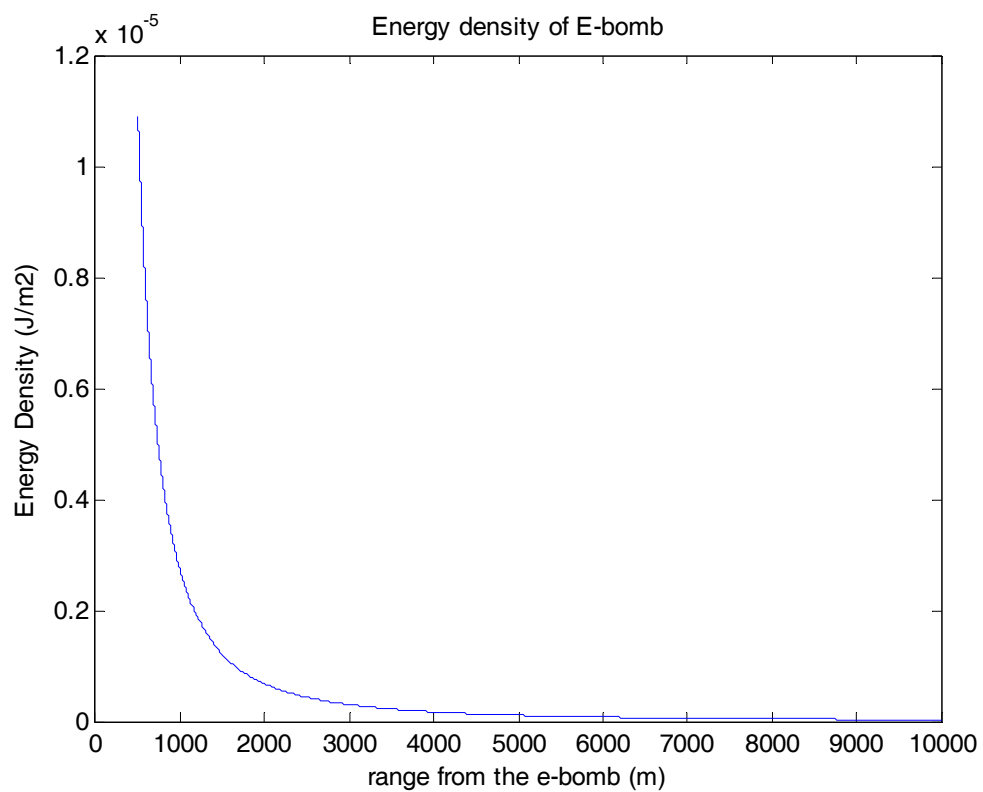


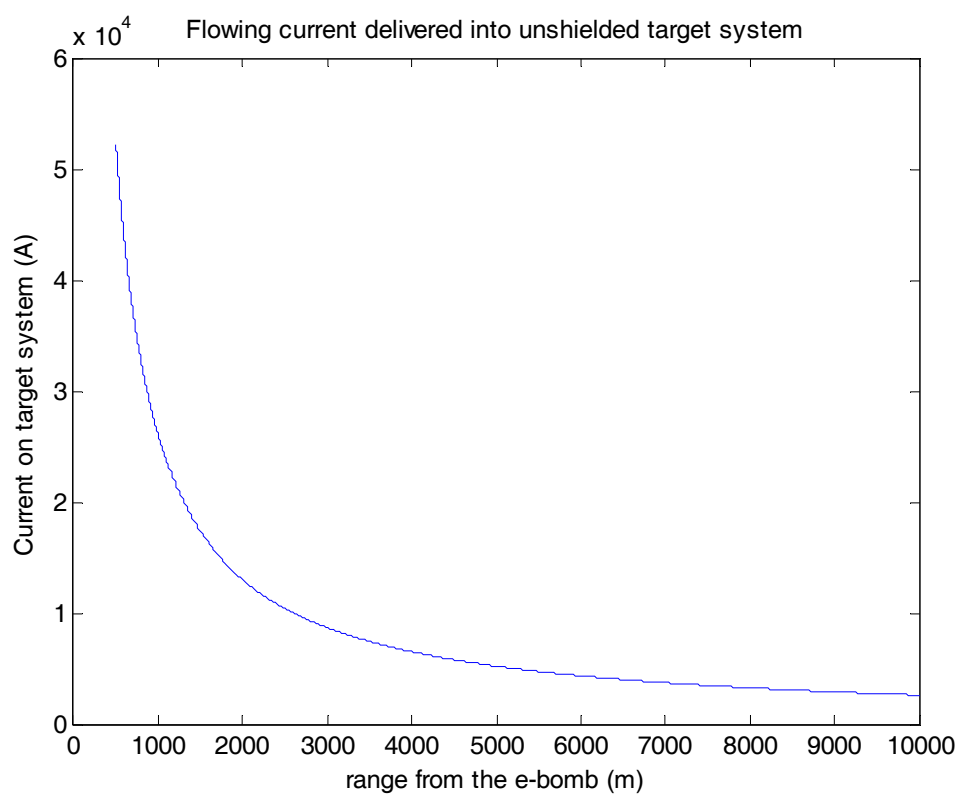
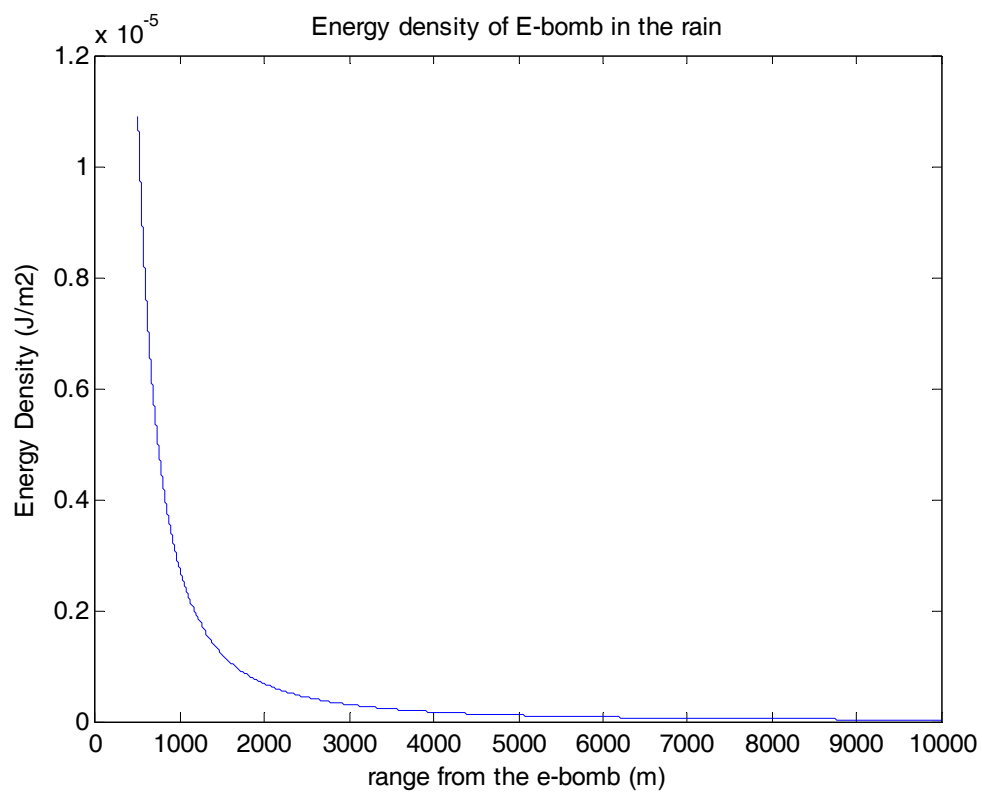


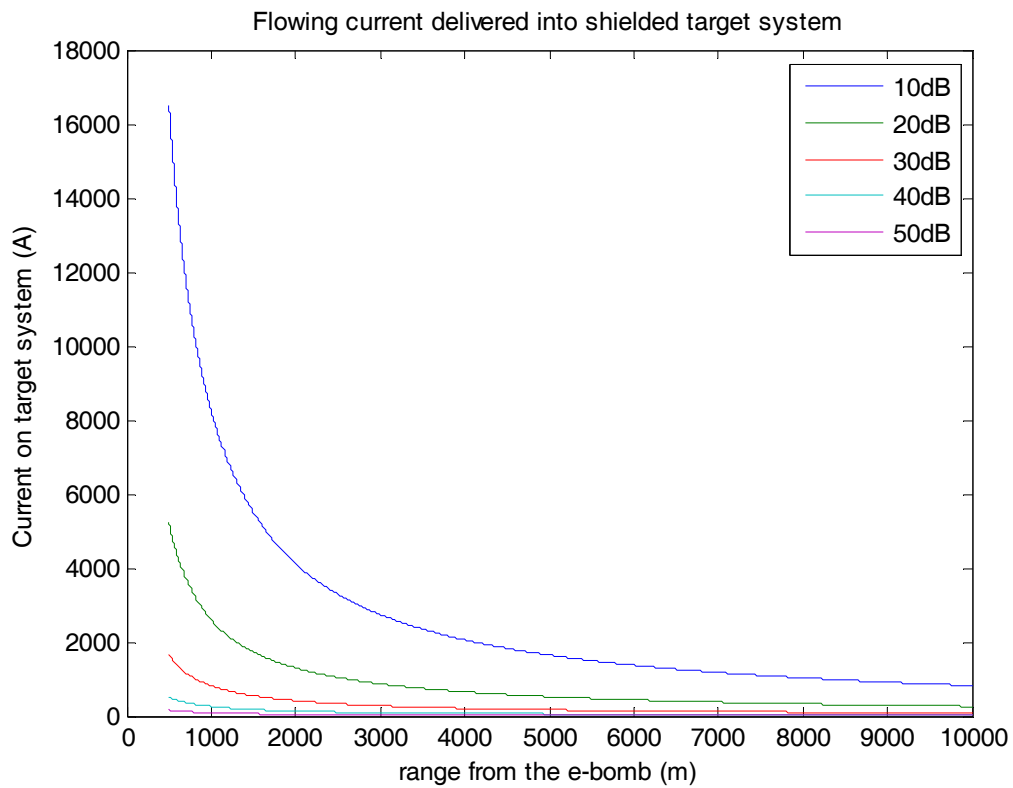
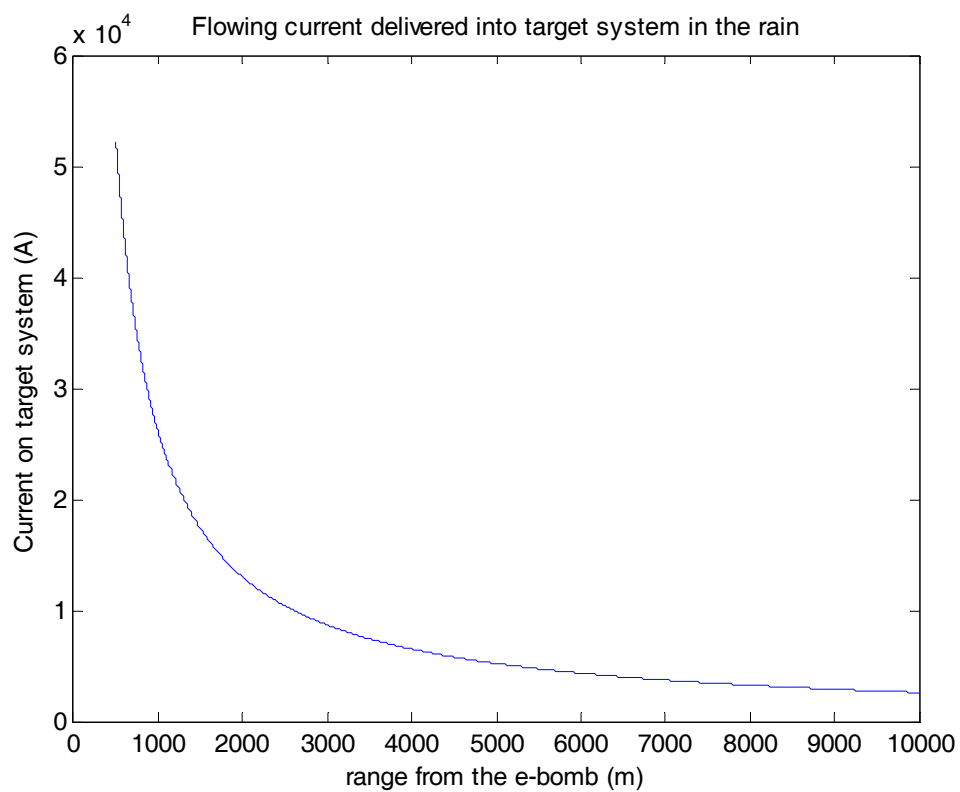
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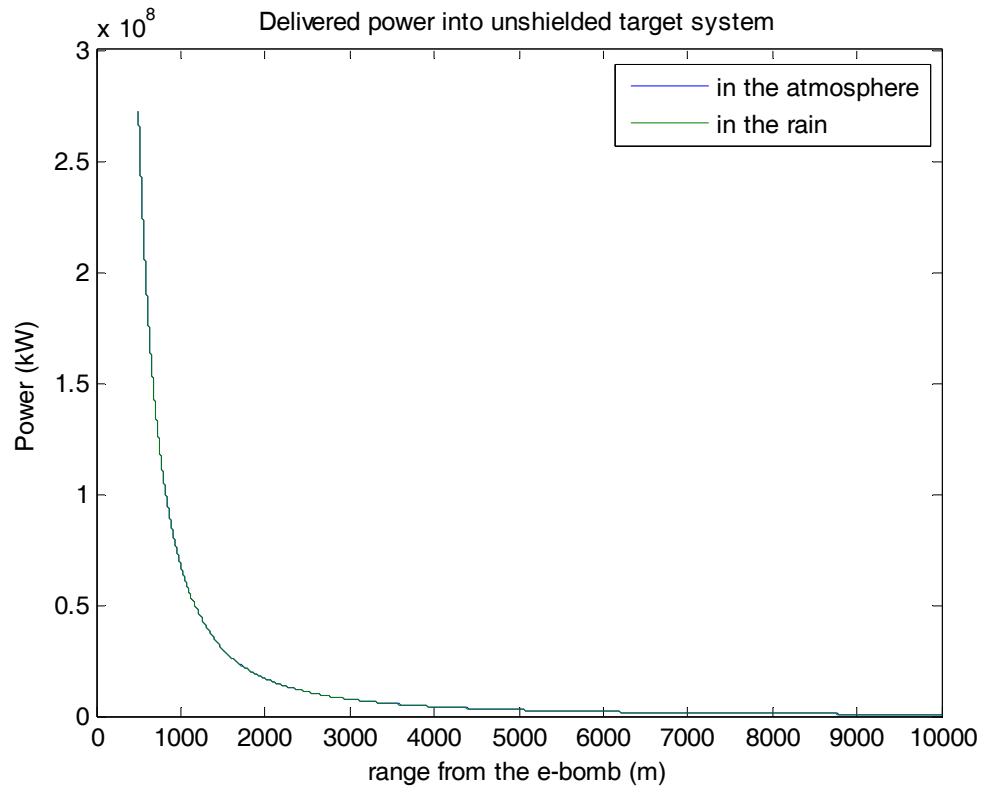
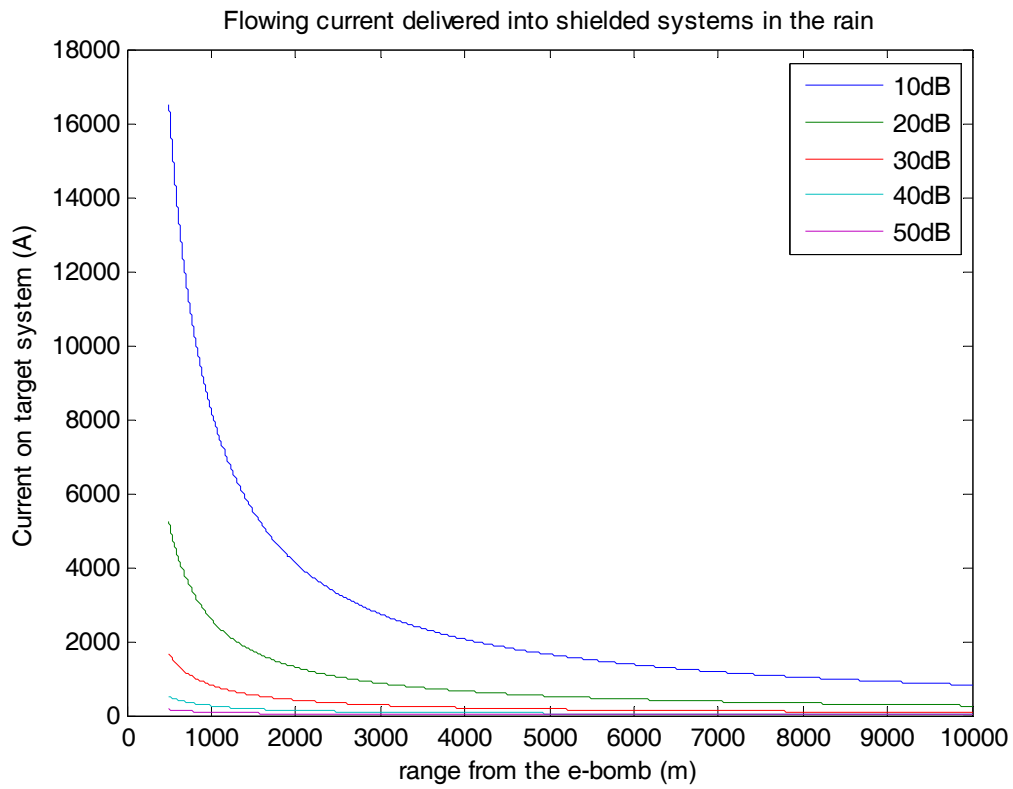


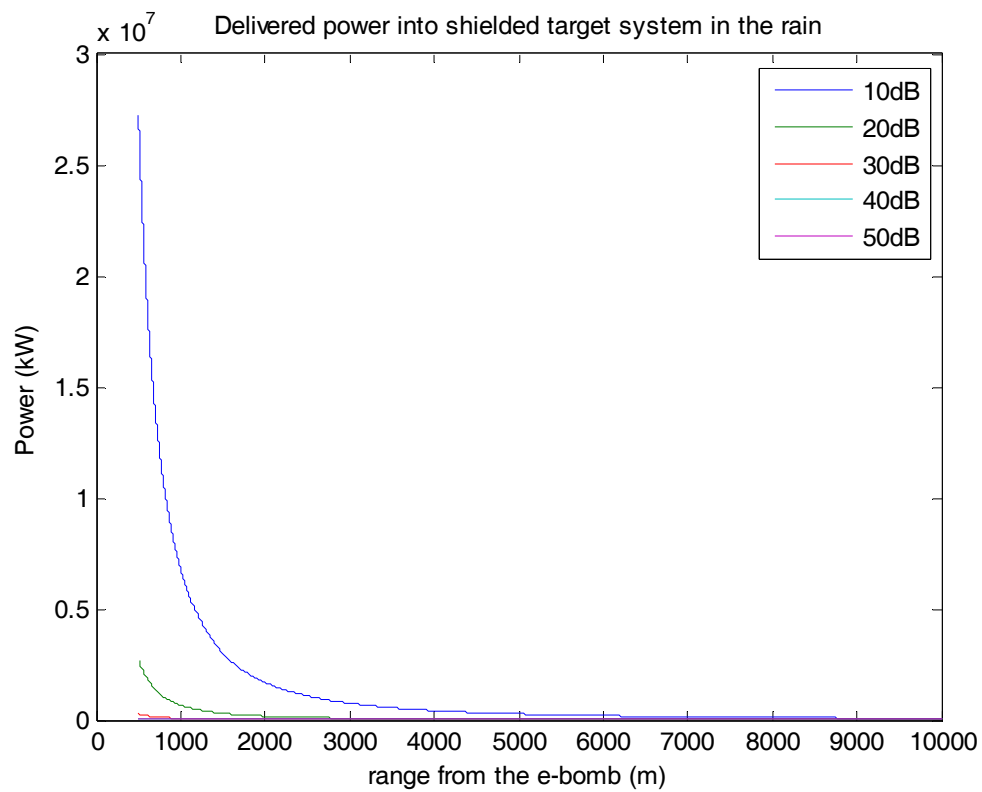
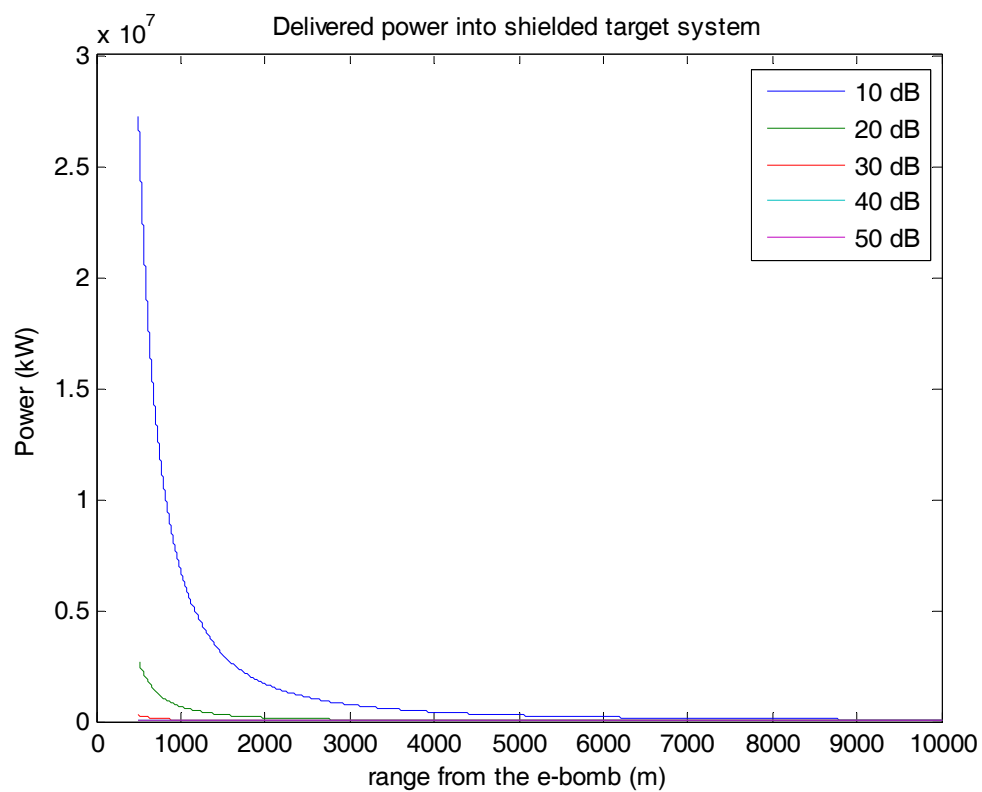












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